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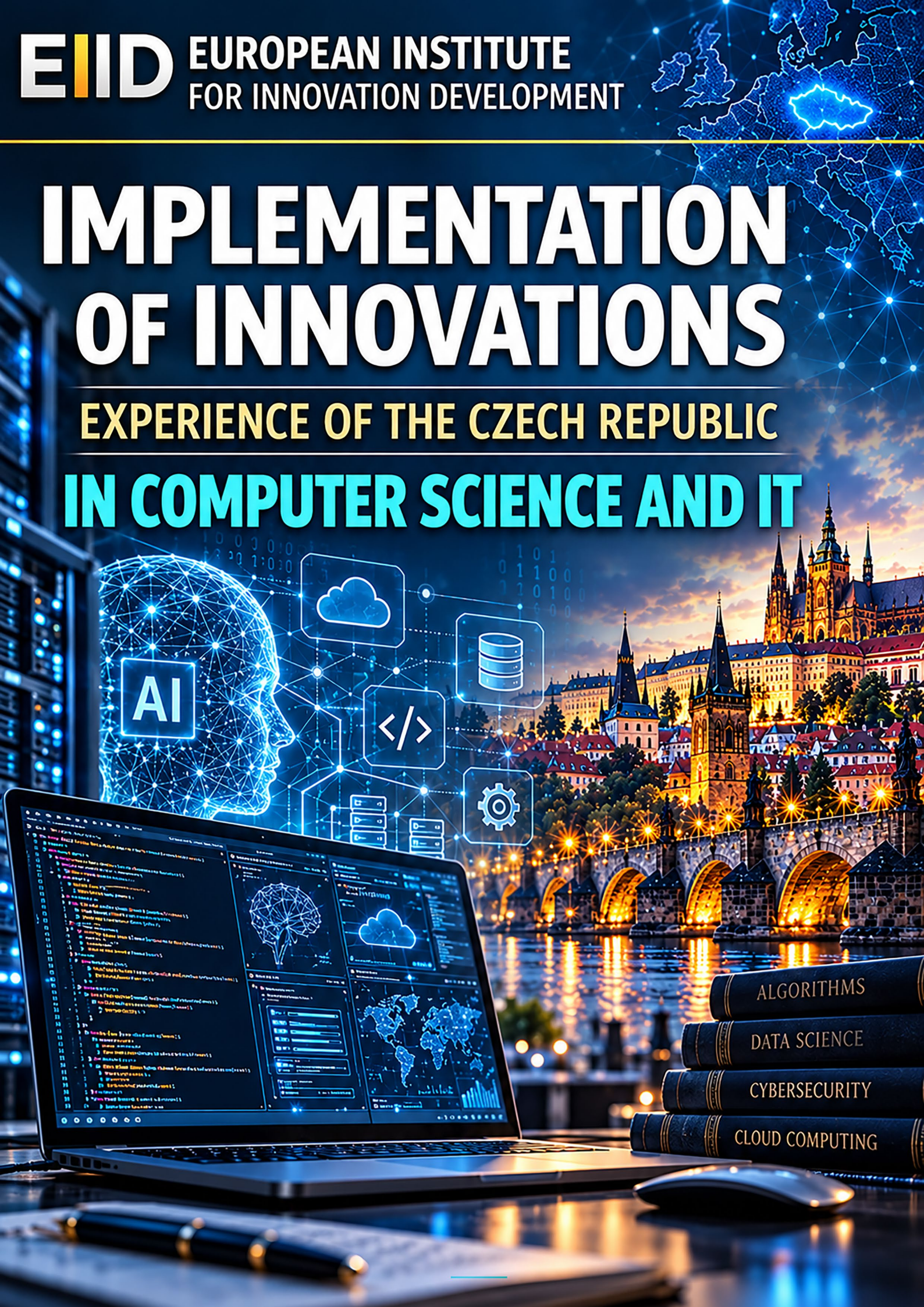
EXPERIENCE OF THE CZECH REPUBLIC

IN COMPUTER SCIENCE AND IT



EUROPEAN INSTITUTE FOR INNOVATION DEVELOPMENT



Implementation of Innovations in Computer Science and IT

Experience of the Czech Republic

Dr. Alexander Buychik

Ostrava–Opava, Czech Republic

2026

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Introduction

Computer Science and Information Technology in Contemporary Czechia: Scientific Traditions, Digital Transformation, Technological Entrepreneurship and European Integration, 1993–2025

The development of computer science and information technology in the Czech Republic between 1993 and 2025 is best understood as the transformation of an established intellectual and technical tradition under new political, economic and international conditions. Independence created a distinctive national framework for research and enterprise, but neither algorithms nor computing institutions appeared for the first time in 1993. Czech researchers and engineers inherited decades of experience in mathematical machines, cybernetics, electronics, automation and scientific computation. They also inherited universities, specialised institutes and professional relationships whose histories reached beyond the boundaries of the new state. During the following thirty-two years, that inheritance was transformed by market competition, widespread internet access, European integration and the growing importance of digital information. The same period witnessed the development of export-oriented software companies, advanced research infrastructure and increasingly sophisticated public digital services. Yet technological progress was neither uniform nor reducible to the success of a small number of famous firms. Fundamental research, engineering competence, entrepreneurial initiative and institutional policy interacted in different ways across regions and decades. This book examines those interactions in order to explain how a country with a substantial industrial and academic legacy became a participant in an interconnected European digital economy. Its central concern is the relationship between continuity and innovation rather than a simple succession of increasingly powerful computers.

The subject requires conceptual precision because computer science, informatics, information technology and the information technology industry describe overlapping but distinct domains. Computer science investigates the theoretical foundations, formal methods and practical principles of computation, including algorithms, data structures, programming languages and the organisation of computational systems. Its results may take the form of proofs, methods, models, software systems or new explanations of what computers can and cannot calculate. Informatics is often used in European academic contexts in a similarly broad sense, although its institutional meaning can place greater emphasis on information, knowledge representation and the interaction between people and computational processes. Information technology (IT) refers more directly to the technical systems through which information is processed, stored, communicated, secured and made available to users. It therefore includes computers, networks, databases, software platforms and the organisational arrangements required to operate them. The IT industry, by contrast, concerns the organisations and markets that develop, sell, integrate, maintain and support such technologies. A university may make an original contribution to

algorithmic theory without producing a marketable application, while a commercial company may create an influential digital service without introducing a new scientific theorem. These activities can reinforce one another, but their achievements must be assessed according to different criteria. The distinctions are essential for a historically credible account of Czech technological development. The definitions adopted here are consequently functional rather than exclusive, since the boundaries of these fields have changed throughout the period under review.

The expression digital transformation introduces a further level of analysis because it describes changes in institutions and social practices rather than a discipline or a particular industry. A factory may use digital control systems to redesign production even when the underlying software was developed elsewhere. A hospital may improve coordination through electronic records without undertaking original computer-science research. Public administrations may offer online procedures whose importance lies in accessibility, institutional interoperability and accountability rather than algorithmic novelty. Conversely, an innovative research result can be significant long before its practical applications become visible. The same technological artefact can therefore be considered from scientific, engineering, economic and social perspectives. These perspectives are related, yet evidence supporting a claim in one cannot automatically establish a claim in another. This book treats the diffusion of digital systems as a historical process while reserving the language of scientific discovery for identifiable contributions to knowledge. Such an approach also prevents changes in consumer habits from being mistaken for a direct measure of national research excellence.

Innovation in the computing field has a particularly varied character, ranging from fundamental concepts to the organisation of complex technological services. An algorithm can be innovative because it solves a recognised problem with better theoretical guarantees or substantially improved computational efficiency. A software architecture may be valuable because it enables reliable operation, security or interoperability at a scale that was previously impracticable. A research infrastructure can transform scientific opportunities without itself representing a theoretical breakthrough. A digital enterprise may innovate through a product, a business model or a method of delivering services to users in different countries. Public-sector innovation may depend instead on legal coordination, organisational redesign and the protection of citizens' rights. These forms of change should not be forced into a single hierarchy based on commercial revenue or publication numbers. Their significance emerges through evidence appropriate to the activity being examined, including peer-reviewed work, reproducible technical results, documented adoption and sustained societal effects. The Czech experience is especially instructive because it contains examples of all these forms of innovation within one comparatively compact national system. This breadth is the reason why the volume combines the history of science with the history of industry and public digital governance.

The antecedents of Czech computing reach into the scientific and engineering culture of Central Europe before the advent of modern electronic computers. Mathematics, electrical engineering, mechanics and technical education created bodies of knowledge that could later be joined in the design of calculating machines and automated processes. Prague developed durable traditions of university teaching and technical experimentation, while other cities contributed industrial

expertise and specialised forms of engineering education. During the twentieth century, the relationship between theoretical mathematics and practical instrumentation became increasingly important. Mechanical and electromechanical devices demonstrated that complex calculation could be embodied in machines, even when their performance was limited by contemporary materials and control systems. The history of this field is consequently broader than a list of electronic computers, because it includes the development of methods for representing, transmitting and manipulating information. Institutions able to educate mathematicians, physicists and engineers furnished the human resources on which later computer laboratories depended. Industrial demand likewise encouraged the search for automated calculation, measurement and control. By the time digital electronics began to transform research internationally, the Czech lands already possessed substantial technical foundations. The national developments after 1993 cannot be explained adequately without recognising this earlier formation of knowledge and competence. This heritage also explains why later developments must be related to the history of scientific training rather than attributed exclusively to the arrival of foreign computer equipment.

Post-war Czechoslovakia played a meaningful role in the early history of computing through the work of Antonín Svoboda and researchers associated with mathematical machines. The development of the SAPO (Samočinný počítač, meaning automatic computer) and later projects illustrates an effort to design computing equipment within local scientific and technological circumstances. Components of the SAPO and EPOS computers survive in the collections of the National Technical Museum, together with other instruments from the history of information processing. These artefacts are evidence of an indigenous engineering tradition rather than proof that the country operated independently of international scientific ideas. Their development required a combination of mathematical reasoning, electronics, mechanical engineering and organisational support. Work on computers also trained specialists whose skills circulated through research institutes, universities and industrial organisations. The significance of these early achievements lies partly in their contribution to technical culture and the transmission of expertise across generations. They should therefore be treated as the historical background to modern Czech computer science rather than as accomplishments of the independent republic. Recognising this distinction enables continuity to be described without inaccurately relocating earlier achievements into the period after 1993. The early computer projects demonstrate, moreover, why the history of computing should preserve evidence of design processes and institutional learning as well as finished machines.

During the socialist decades, computing developed within a political economy that differed substantially from the market-oriented environment created after 1989. State institutions and industrial organisations could support substantial programmes in automation, scientific calculation and electronic engineering. At the same time, restrictions on international exchange, the organisation of production and access to modern components influenced which technologies could be developed and deployed. Research communities responded with combinations of local expertise, adaptation and participation in the scientific networks available to them. Computing was used in technical design, industrial management, academic calculation and other specialised functions before it became an ordinary household technology. In many

settings, access to powerful machines remained concentrated in institutions rather than distributed among individual users. The period consequently produced both accumulated competence and structural constraints that shaped the transition of the 1990s. Historical analysis should avoid portraying this inheritance either as a uniformly successful national tradition or as an intellectually empty system. Its actual significance becomes apparent through the institutions, skills and unresolved technological limitations that survived into the new era.

Universities and research institutes provided the strongest bridge between the Czechoslovak computing tradition and the independent Czech scientific system. Charles University and the Czech Technical University in Prague developed complementary strengths in mathematics, theoretical inquiry, software-related disciplines and engineering. Masaryk University and technical education in Brno cultivated additional research communities, while regional institutions supplied specialists for public services and industrial practice. The Academy system sustained specialised research that could extend beyond the time horizons of individual teaching programmes or commercial projects. Computer science also benefited from its proximity to mathematical logic, statistics, control theory, information theory and signal processing. These relationships matter because the field rarely develops through isolated technical inventions. New algorithms depend on mathematical ideas, and reliable applications depend on knowledge of physical systems, communication networks and human requirements. Doctoral education and scholarly collaboration preserve such knowledge even when administrative structures are repeatedly reorganised. After 1993, the survival and renewal of these academic communities became an essential precondition for participation in international computer science. Institutional continuity was therefore not an obstacle to innovation but one of the resources through which it could become sustainable.

The political transformation beginning in 1989 changed the intellectual opportunities available to computing researchers and engineers before the Czech Republic formally gained independence. Greater freedom of travel and communication allowed more direct contact with Western universities, conferences, professional associations and technology suppliers. Access to international journals, programming environments, hardware and emerging networks gradually altered the methods available to research groups. It also exposed domestic institutions to new expectations concerning competitiveness, external evaluation and the relevance of their training programmes. In the broader economy, market liberalisation created conditions for the establishment of privately owned software firms and service providers. Entrepreneurial activity thus began to complement forms of technical work previously concentrated within public institutions and state enterprises. These changes did not remove structural disadvantages immediately, and opportunities varied considerably across organisations and individuals. Nevertheless, the period after 1989 opened new channels through which inherited technical expertise could interact with international technological developments. The establishment of an independent state in 1993 subsequently provided a different legal and administrative framework for developments already under way.

The year 1993 was a watershed in governance rather than a moment of technological creation from nothing. The dissolution of Czechoslovakia required universities, public research organisations and government bodies to operate within a separate Czech system of legislation,

financing and international representation. The Czech Academy of Sciences (CAS) became an important institutional framework for the continuation of specialised research inherited from the former federal academic structure. Research units concerned with information theory, automation and computer science could preserve knowledge while adapting to new forms of assessment and support. Competitive grants, academic self-government and international cooperation gradually acquired increasing importance within the national research environment. Technical universities similarly had to revise educational priorities as demand for software developers, network engineers and information specialists expanded. The relationship between public research and private enterprise also changed as commercial organisations became important employers and partners. These developments influenced the direction and organisation of scientific work without determining the correctness or originality of individual results. The history of modern Czech computer science is thus simultaneously a history of institutional reconstruction and of new intellectual opportunities. Any evaluation of the period must distinguish the legal creation of the Czech state from the considerably older emergence of its computing disciplines.

The expansion of computer networking illustrates how early digital transformation crossed the boundary between research infrastructure and wider economic development. Czechoslovakia was formally connected to the internet on 13 February 1992 at the Czech Technical University in Prague, before the establishment of the independent Czech Republic. On 15 June 1993, the national CESNET (Czech Educational and Scientific Network) backbone began operating with centres in Prague and Brno. Its initial connection was modest by later standards, but the network established a basis for systematic communication among universities and research organisations. In 1996, the CESNET association was created to take over network operation and support the development of national academic connectivity. Research networking improved the circulation of information, enabled contact with international collaborators and provided experience with digital infrastructure management. The same environment encouraged skills in networking, security, distributed systems and the operation of reliable services. Commercial internet access developed alongside this academic foundation rather than replacing it immediately. Consequently, the internet's Czech history should not be reduced to the rapid growth of commercial websites in the late 1990s. The earlier role of universities and network specialists demonstrates how publicly supported knowledge infrastructures can establish conditions for later private-sector innovation. Its early history also underlines the distinction between the creation of a network and the establishment of the organisations responsible for its continuing operation.

The emergence of a commercial internet economy created new possibilities for translating technical knowledge into services directed towards ordinary users. Seznam.cz, launched by Ivo Lukačovič in 1996, illustrates the development of a domestic internet platform in an environment where access and familiarity were still limited. Its progression from a directory of websites towards search and other services reflected growing demand for information organised in the Czech language. Internet firms had to confront problems that differed from those of academic computing, including user acquisition, advertising, reliability and competition for public attention. Software production also became increasingly export-oriented because digital

products could reach users beyond the relatively small domestic market. The distinction between a technically competent application and a commercially sustainable enterprise therefore acquired practical importance. Entrepreneurs combined engineering knowledge with financing, product design and the ability to adapt to changing customer expectations. The market successes of this period should nevertheless be assessed through their documented history rather than treated as inevitable outcomes of national talent. They reveal how the opening of technological markets created opportunities that were distributed unevenly among firms and regions. The practical capacity to serve Czech-speaking users became an important form of technological differentiation in an increasingly international market.

Cybersecurity provides one of the clearest examples of continuity between technical capabilities originating before independence and internationally visible Czech digital enterprise. The company that later became known as Avast traces its origins to work begun in Prague by Pavel Baudiš and Eduard Kučera in 1988. Its development subsequently connected programming, knowledge of malicious software, product distribution and global consumer demand. This trajectory demonstrates that a firm operating successfully after 1993 may have intellectual and organisational roots in the final years of Czechoslovakia. Security technology also raises questions that are scientific and engineering-oriented as well as commercial. Detecting threats requires methods of analysis, dependable software design and the ability to adapt to rapidly changing adversarial behaviour. Market expansion alone does not establish that every component of a product represents original research, but neither should applied engineering achievements be dismissed because they are commercial. Czech participation in this sector would later become important to debates about digital resilience and strategic technological capacity. Its history exemplifies the need to connect individual company narratives with the broader evolution of cybersecurity knowledge.

Fundamental computer science continued to develop within institutions whose contributions are not adequately described through the growth of the software market. The Institute of Computer Science of the Czech Academy of Sciences identifies theoretical computer science, artificial intelligence and interdisciplinary data science among its areas of research. The Institute of Information Theory and Automation combines work in artificial intelligence, systems science, applied mathematics, and signal and image analysis. Such organisations represent research traditions in which conceptual originality, methodological rigour and scholarly publication carry particular weight. Their results may also support applications in medicine, environmental studies, energy and industrial systems. Yet the path from a theoretical idea to a practical application is rarely immediate or linear. Universities and Academy institutes contribute through research groups, specialised seminars, doctoral supervision and international collaborations as well as through individual publications. The existence of these complementary institutions has allowed Czech computer science to remain broader than the demands of any one technological market. Their achievements must therefore be considered through identifiable research questions and results rather than inferred from national expenditure on information technology. This distinction is particularly important when comparing a scientific institute with an export-oriented software company.

Language technologies demonstrate an especially distinctive connection between Czech intellectual traditions and modern computation. Research into natural language processing requires mathematical methods, linguistic analysis, annotated datasets and the engineering of practical tools. Czech presents questions involving rich inflection, word order and linguistic structure that have helped motivate sophisticated computational approaches. At Charles University, the Institute of Formal and Applied Linguistics developed resources associated with the Prague Dependency Treebank, whose annotation work began in the 1990s. Such corpora support the study of grammatical relations, machine learning and methods for processing human language. Their value lies not merely in making texts searchable, but in providing systematically structured evidence that can support reproducible scientific investigation. The development of language resources also contributes to the preservation and accessibility of cultural knowledge in a digital environment. Czech computational linguistics thus provides an example in which national linguistic specificity becomes relevant to research of international significance. It illustrates the productive interaction between informatics, philology and research infrastructure without conflating the disciplines themselves.

The accession of the Czech Republic to the European Union (EU) in May 2004 substantially altered the institutional opportunities available to computer-science researchers and digital enterprises. European research programmes created broader possibilities for partnerships, mobility and projects involving institutions in several countries. Shared technical standards and a larger market encouraged firms to consider the interoperability and international reach of their products. European integration also influenced the regulatory environment surrounding data, electronic communications, competition and digital public services. Its effects were not identical in fundamental science, university education, infrastructure construction and private business. Some research groups benefited primarily from collaboration, while others gained access to equipment, funding or large-scale shared facilities. For companies, the relationship between integration and growth depended upon their products, investment arrangements and competitive capabilities. Membership in European structures therefore provided opportunities rather than an automatic explanation for every technological achievement. The analysis must establish which programmes or relationships contributed to particular outcomes. This approach gives European integration its proper historical significance without neglecting domestic institutions and individual agency.

Digital government and the spread of information systems in public administration constituted another dimension of transformation after the early internet period. The operation of electronic registers, secure communication channels and online services requires technical systems that are also dependent on legislation and administrative coordination. Public digital services can improve convenience and transparency, but their effectiveness must be demonstrated through accessibility, reliability and actual use. A system may be technically sophisticated while remaining difficult for citizens or public employees to navigate. Equally, digitising an existing procedure does not always simplify the underlying organisation of public administration. Such differences explain why the history of electronic government requires a broader methodology than the history of computer hardware or software engineering. National statistical publications now distinguish digital infrastructure, enterprise technology, public administration, education

and health services rather than representing these activities as a single measure. In the Czech Republic, the relationship between technical implementation and public trust became increasingly important as digital services expanded. The integration of electronic identification and secure information exchange also brought issues of privacy, interoperability and accountability to the foreground. Digital transformation should therefore be evaluated in terms of institutional effectiveness and citizens' experiences as well as technological deployment. For these reasons, indicators of online service availability must be considered alongside evidence concerning the practical completion of administrative tasks.

The 2010s brought an important change in the scale of computational resources available to Czech research through new high-performance computing (HPC) infrastructure. The IT4Innovations National Supercomputing Center in Ostrava introduced the Anselm system in 2013 and the Salomon system in 2015. These developments expanded possibilities for computationally intensive projects in science, engineering and the analysis of large datasets. Computational infrastructure matters because some research questions become feasible only when algorithms, hardware and specialist support are available together. Supercomputing is not equivalent to computer-science discovery, but it can create the conditions in which new methods are tested and scientific models investigated. The demands of operating large systems also stimulate expertise in parallel programming, scheduling, storage and computational efficiency. Researchers in other disciplines consequently become participants in a broader digital scientific environment. Through such infrastructures, national scientific capacity can be strengthened without requiring every institution to maintain comparable resources independently. The development of advanced computing in Ostrava also demonstrates that the technological geography of the Czech Republic extends beyond Prague and Brno.

The growth of research infrastructure became increasingly networked as communication, computation and data storage were brought together in complementary systems. The national e-INFRA CZ initiative links CESNET, the CERIT Scientific Cloud and IT4Innovations in a framework supporting research and education. These partners contribute different capabilities, including high-capacity communication, distributed computing, cloud resources and supercomputing. Their cooperation reflects the fact that scientific data must be moved, stored, protected and processed through interconnected services. It also changes how researchers in less computationally specialised disciplines can use advanced technologies. A life-sciences project may require secure transfer of large datasets, while a physics simulation may depend upon access to substantial processing resources. Shared infrastructure is consequently both a technical achievement and an organisational model for supporting knowledge production. Its contribution is measured through research opportunities, reliable operation and participation in wider scientific networks, not simply by the purchase of machines. The Czech experience illustrates the gradual integration of computing infrastructure into the everyday conditions of modern scientific work. It also demonstrates how digital technologies can become a cross-disciplinary public research resource.

Cybersecurity acquired a more explicit institutional character as digital networks became indispensable to government, industry and critical public services. Czech legislation on cybersecurity in 2014 provided an important foundation for a more systematic national approach

to risk and protection. The National Cyber and Information Security Agency (NÚKIB) was established on 1 August 2017 as a central administrative authority with responsibilities in this field. Its creation should be distinguished from the earlier emergence of commercial security companies and from university research on cryptography or network protection. Public authorities address questions of coordination, regulation and national preparedness that cannot be resolved through the sale of individual security products. Research institutions, commercial developers and government agencies nevertheless depend upon overlapping pools of technical expertise. Cybersecurity also challenges simple ideas of technological progress because a more complex digital society may create new forms of vulnerability alongside new capabilities. The strength of a national system therefore depends upon risk assessment, skilled personnel, institutional cooperation and the capacity to respond to changing threats. This dimension becomes increasingly important when considering the relationship between digital growth and the resilience of the state.

The Czech software and digital-services economy developed beyond antivirus products and internet search into a diversified set of entrepreneurial activities. Domestic firms and Czech-founded enterprises participated in enterprise software, data services, online marketplaces, educational technologies and specialised business applications. Video-game development became another visible field in which software engineering interacted with computer graphics, interactive design and international consumer markets. These sectors differ considerably in how they finance development, organise intellectual property and measure success. Their shared feature is an ability to transform technical work into products whose users may be located far beyond the Czech Republic. The internationalisation of a company can involve foreign subsidiaries, acquisitions or changes in ownership that complicate straightforward national classifications. An enterprise founded in Czechia remains historically relevant even when its subsequent corporate structure becomes international. Conversely, a foreign company's research laboratory located in Czechia may contribute strongly to local expertise without becoming a Czech-founded business. Understanding the national IT industry consequently requires more than compiling corporate names and headline valuations. This book examines enterprise histories as evidence of economic and technological change while avoiding uncritical claims of national ownership over global commercial success.

The coronavirus pandemic accelerated certain forms of digital adoption after 2020 while revealing limitations that earlier indicators could conceal. Remote work, online education and digital service provision increased the practical importance of reliable connectivity and accessible platforms. Existing networks and institutional information systems became indispensable to maintaining research collaboration and everyday organisational activity. The experience also demonstrated that digital tools do not automatically guarantee good educational outcomes, efficient management or equal access. Organisations with established technical capacity could often adjust more readily than those requiring rapid investments or staff training. Cybersecurity risks and the protection of personal information became more consequential as activities moved across domestic, institutional and cloud-based environments. For researchers, international collaboration depended increasingly on digital channels even when physical access to laboratories and facilities was restricted. The pandemic thus serves as a case through which

the interaction between technological preparedness and institutional resilience can be examined. It also warns against interpreting temporary increases in digital usage as sufficient evidence of lasting structural innovation.

The final years of the period were marked by increasing interest in artificial intelligence (AI), machine learning, quantum technologies and data-intensive computation. These developments connected established Czech strengths in mathematics, information theory, language processing and software engineering with rapidly changing international research agendas. Advanced models require not only computing power but also reliable data, evaluation methods, specialist skills and appropriate governance. Generative systems made the capacities and limitations of machine learning more visible to researchers, firms and public institutions. At the same time, European debates about data protection, safety and technological autonomy began to influence the conditions under which new products could be developed and deployed. Research on future computing architectures and quantum information acquired growing strategic visibility, although exploratory work should not be equated with mature commercial technologies. Large-scale computational facilities became important to some of these investigations, while theoretical computer science continued to pursue questions independent of immediate industrial application. The Czech response was shaped by inherited expertise and international cooperation rather than by an abrupt replacement of earlier disciplines. By 2025, these emerging fields represented an important frontier of national technological ambition, but their long-term economic and scientific outcomes remained partly uncertain. The book therefore distinguishes established achievements from plans, experimental capabilities and expectations about future technological change.

Evidence available by 2025 shows a digital economy with considerable strengths and persistent structural limitations. The Czech Statistical Office's Information Society in Figures 2025 documents the use of digital technologies across infrastructure, households, enterprises, public administration, education and healthcare. Such coverage is valuable because it prevents attention from concentrating solely on major technology companies or specialised research centres. The European Commission's 2025 Digital Decade assessment identifies comparatively strong basic digital skills and broad fifth-generation mobile network coverage as positive characteristics of Czechia. The same assessment points to limitations in very high-capacity connectivity and the digital transformation of businesses. These findings demonstrate that a country may possess internationally visible software enterprises while confronting weaknesses in the general diffusion of advanced technologies. Strong research centres do not automatically eliminate differences between large firms and smaller enterprises or between technically specialised workers and the broader population. Similarly, successful public platforms cannot be assumed to resolve all problems of access, interoperability and trust. Digital development must consequently be understood as uneven and multidimensional rather than as a single ranking of national progress. Quantitative evidence provides essential context, but its interpretation requires attention to definitions, measurement dates and the specific phenomena being compared. This balanced interpretation is essential for distinguishing national technological visibility from the wider and more demanding process of digital modernisation.

The geographical organisation of Czech computer science also complicates an exclusively capital-centred account. Prague concentrates major university departments, Academy institutes, software enterprises and institutions concerned with national digital governance. Brno has become a powerful environment for technical education, informatics, cybersecurity research and commercially oriented technological activity. Ostrava has acquired a distinctive profile through advanced computing infrastructure and its connections with engineering and scientific applications. Other university cities contribute through regional research groups, specialised programmes, digital businesses and technical education. The prominence of individual centres should not obscure the flows of researchers, students, funding and knowledge between them. National capacity develops through both strong local specialisations and effective opportunities for cooperation. Regional differences in investment, labour markets and access to infrastructure nevertheless shape which research and industrial activities can be sustained. A geographically differentiated perspective is therefore necessary to understand both the resilience and the inequalities of the Czech digital ecosystem.

The method adopted in this book brings together historical reconstruction, disciplinary analysis, institutional comparison and the study of innovation systems. Historical reconstruction establishes when institutions, programmes, technologies and enterprises actually emerged, while distinguishing the Czechoslovak inheritance from developments after independence. Disciplinary analysis examines the substance of algorithms, methods and research problems rather than relying upon general claims of excellence. Institutional comparison investigates how universities, Academy institutes, state agencies, shared infrastructures and private companies undertake different functions. Innovation-system analysis considers the transfer of knowledge between these actors and the conditions under which scientific results influence technological practice. Evidence is drawn from scholarly publications, official institutional histories, research reports, statistical series, company records and European policy documents. Each source category has limitations, and corporate narratives or institutional promotional materials are not treated as independent proof of scientific originality. Numerical indicators are interpreted according to their definitions and the years to which they refer. Particular care is taken to distinguish a project announcement from an operational facility and a research hypothesis from a demonstrated achievement. This combination of methods supports a critical account intended for scientific readers without sacrificing accessibility to an interdisciplinary audience.

The attribution of national achievement presents difficulties because computing is an exceptionally international field. A researcher may be educated in Prague, employed in another country and collaborate on a result with authors from several institutions. A company may be founded in Brno, develop its software in multiple states and later become part of an international corporate group. A supercomputer located in Ostrava may support research whose principal scientific authors are based abroad. These circumstances mean that institutional location, personal nationality, corporate ownership and intellectual contribution must be considered separately. Where a specific result is examined, the discussion seeks evidence of the contribution made by Czech-based researchers, teams or organisations. International collaboration is treated as a genuine component of the national research environment rather than as evidence of diminished local achievement. At the same time, participation in a large

consortium is not automatically described as the origin of every result produced by that consortium. A careful account must identify what was invented, developed, operated or implemented, and by whom. This distinction makes it possible to recognise the Czech contribution accurately while respecting the collective character of modern computer science. The resulting evaluation seeks to illuminate identifiable contributions rather than to construct an artificial national ranking of internationally shared achievements.

The boundaries of the investigation are chronological as well as conceptual. The years 1993–2025 define the main period, while earlier Czechoslovak developments are introduced when they explain scientific or institutional continuity. Events after 2025 are not used to redefine the achievements attributed to the period under examination. The narrative proceeds first through the historical stages of national transformation and then through major research directions, commercial developments and institutional environments. This organisation enables the same technological phenomenon to be examined from different perspectives without repeating a single account under different headings. The discussion also recognises that the consequences of fundamental research often emerge years after publication and that business outcomes can change rapidly. Historical interpretation therefore avoids claiming that every innovation produced immediate benefits or that all emerging technologies had reached maturity by the endpoint. The aim is to describe a changing system of knowledge, capability and application with appropriate attention to uncertainty. Computer science and information technology in contemporary Czechia ultimately demonstrate how older scientific traditions can be renewed through open institutions, international exchange and technologically ambitious enterprise.

Part One

Historical Evolution of Computer Science and Information Technology in the Czech Republic, 1993–2025

1993 as a Watershed: The Czechoslovak Computing Legacy and the Formation of an Independent Czech Information Technology System

The establishment of the independent Czech Republic on 1 January 1993 altered the institutional framework of computing without bringing Czech computer science into existence for the first time. Universities, research institutes, engineers and mathematicians entered the new state with knowledge accumulated during several decades of Czechoslovak scientific and industrial development. Some of this inheritance consisted of functioning equipment and technical documentation, while another part survived in research methods, specialised training and professional communities. The political opening begun in November 1989 had already changed access to foreign colleagues, scientific literature and computer technologies before the division of the federation. Independence nevertheless required new decisions concerning research governance, institutional finance, university organisation and the relationship between public science and private enterprise. These decisions occurred during a wider shift from large centrally administered technical systems towards competitive markets, decentralised computing and increasingly international information networks. For that reason, the decisive historical question is not when the first Czech computer appeared, but how a pre-existing computing culture adapted to substantially different conditions after 1993. An accurate account must also distinguish scientific ideas, engineering prototypes, industrial production and routine computer use, because their histories did not always advance at the same pace. It must distinguish developments occurring in the Czech lands from achievements produced elsewhere in the former federation, while recognising that the two communities had shared institutions and expertise. The period surrounding independence can consequently be understood as a watershed in institutional responsibility, technological opportunity and intellectual exchange rather than a complete break with the past. This chapter reconstructs the foundations of that transition in order to explain the resources and constraints with which the new Czech information technology system began.

Long before electronic computers became available, mathematical calculation and precision engineering had established an important place within the scientific culture of the Czech lands. The development of technical higher education in Prague and Brno supported the training of specialists capable of moving between mathematics, electrical engineering, mechanics and industrial measurement. These disciplines provided the conceptual basis for analysing control systems and for treating complex calculations as procedures that machines might perform. The distinction matters because the history of computer science extends beyond the appearance of a particular electronic apparatus. It includes efforts to formalise problems, specify sequences of

operations and create instruments that extend human capacity to calculate and organise information. During the interwar period, technical research and industrial modernisation generated practical demands for accurate computation in engineering, manufacturing and public administration. The Second World War interrupted normal academic and industrial development, but it also brought some Central European specialists into contact with rapidly advancing international techniques of calculation and instrumentation. After 1945, rebuilding industrial capacity and modernising scientific methods made automated computation an increasingly plausible national ambition. This ambition rested on a combination of mathematical education, engineering expertise and scientific curiosity rather than on an already mature computer industry. Thus, the later achievements of Czechoslovak computing drew upon a deeper intellectual infrastructure whose origins cannot be reduced to the beginning of the socialist period.

Antonín Svoboda provides a particularly instructive example of the international and interdisciplinary character of the earliest Czechoslovak computer projects. Before the war, his research had addressed technical problems that required mathematical modelling and mechanical methods of calculation. During the war he worked in the United States on computing mechanisms and related instrumentation, acquiring experience that was uncommon in the post-war Czechoslovak research environment. He returned to his homeland in 1946 with the intention of developing domestic capacity in advanced computing technology. His subsequent activities connected mathematical theory, electrical engineering, the construction of computing devices and the organisation of specialist research teams. A laboratory for mathematical machines took shape in Prague around 1950 within the institutional world of mathematical research. The undertaking required not only conceptual design but also people who could manufacture components, assemble prototypes and diagnose technical failures. Svoboda's career therefore illustrates the difference between recognising the future importance of computers and creating the material conditions necessary to build them. It also shows why the history of Czech computing must take account of transnational scientific circulation even when the principal technological projects were situated inside Czechoslovakia.

The early project known as SAPO (Samočinný počítač, meaning automatic computer) gave a concrete form to this national ambition. Developed by a team associated with Svoboda, the machine entered operation in 1957 after a prolonged and technically demanding construction process. SAPO used electromechanical relays at a time when electronic technologies were advancing rapidly in leading computing centres abroad. Its design nevertheless incorporated unusually serious attention to the reliability of computation and the possibility of detecting hardware failure. The system employed replicated elements and a voting principle intended to reduce the consequences of certain component errors. This approach is historically significant because reliable computation is not merely a question of calculating quickly, but also of deciding whether a result can be trusted. The machine consequently demonstrates that technical originality can appear within an apparatus whose components are constrained by economic or industrial circumstances. At the same time, SAPO did not establish an extensive commercial market for domestically produced computers or remove the country's dependence on suitable components. Its experience exposed the gulf between a sophisticated research concept and the

sustained industrial capacity required for regular manufacture. The project became an important source of engineering knowledge even though its practical service life remained limited. Assessing SAPO requires recognition of both its innovative design and the institutional and technological difficulties that restricted its wider effects.

The subsequent EPOS (Elektronický počítací stroj, meaning electronic calculating machine) programme reflected the attempt to move beyond relay-based calculation towards a more advanced electronic computer architecture. Researchers developed design ideas intended to improve performance, flexibility and the general usefulness of automatic computation. The project demonstrated that the early Czechoslovak school possessed ambitions extending beyond the reproduction of existing foreign devices. Yet improvements in design did not guarantee that an industrial enterprise could supply machines at the expected scale or within a planned timetable. The relationship between research organisations and manufacturing ministries became one of the decisive constraints on the programme's development. Delayed components, inconsistent priorities and restricted production capacity weakened the possibility of translating laboratory success into widespread deployment. These difficulties deserve analytical attention because they arose within the organisation of innovation rather than solely from the ingenuity of individual engineers. The experience of EPOS also cautions against describing computer history as a simple procession of increasingly powerful devices. Research prototypes, standardised products, technical maintenance and user training belong to different stages of technological development. The legacy of EPOS is therefore best understood through the interaction of scientific ambition, engineering achievement and the limits of the prevailing production system.

The institutional environment surrounding these projects changed as mathematical-machine research became more specialised within Czechoslovak science. The Czechoslovak Academy of Sciences, established in 1952, created a framework in which long-term research programmes could acquire dedicated organisational structures. The work associated with Svoboda contributed to the emergence of specialised laboratories and the Research Institute of Mathematical Machines. Such organisations assembled mathematicians, electronics specialists, designers and programmers in teams capable of pursuing complex technological objectives. Their work could not be conducted through individual expertise alone because building a functioning computer required coordination across several professions. Institutional specialisation also created mechanisms for transmitting practical knowledge between successive engineering projects. Nevertheless, organisational restructuring sometimes separated scientific work from the industrial conditions needed to apply its results. The transfer or reclassification of research groups could change access to equipment, ministerial support and the priorities of subsequent programmes. By the time the independent Czech Republic was formed, the legacy of these experiences included an awareness that institutions could preserve knowledge while simultaneously limiting technological flexibility.

Cybernetics provided a broader intellectual framework for the development of information processing, communication and control in post-war Czechoslovakia. Its conceptual territory included feedback, regulation, information, mathematical models and the behaviour of complex technical or biological systems. This breadth gave the subject unusual potential to connect

engineers with mathematicians, economists, physicians and other researchers. However, the early socialist political environment did not consistently welcome cybernetics as a legitimate scientific approach. Ideological suspicions during the 1950s created difficulties for researchers seeking to discuss ideas that were associated with Western scientific movements. The gradual rehabilitation of cybernetics later permitted more systematic research organisation and a more visible professional community. These changes did not erase political control, but they enlarged the scope for studying automation and information within recognised academic institutions. In 1959, the Institute of Information Theory and Automation was established through the combination of departments concerned with automation and information theory. Its formation demonstrated that cybernetics-related research had acquired sufficient scientific and institutional standing to support a dedicated Academy institute. The institute subsequently developed approaches connecting mathematical theory with practical problems in control, communication and decision-making. By 1993, these traditions represented an essential component of the emerging Czech computer-science landscape, even though they were not identical to the engineering of computer hardware.

The development of information theory and automatic control illustrates why early computing cannot be studied solely through the machines produced by industrial enterprises. A theory of information concerns the representation, transmission and limitations of messages rather than the manufacture of one specific computer. Control theory investigates how systems can be observed, regulated and stabilised under conditions that may include uncertainty or incomplete knowledge. Both fields became increasingly dependent upon mathematical models and, later, computational implementation. Czechoslovak researchers contributed to questions concerning communication channels, self-adjusting controllers and the modelling of large technical networks. Work undertaken at the Institute of Information Theory and Automation before 1990 included internationally recognised investigations of channels with memory and algebraic control systems. Such results possessed intellectual significance independently of whether they immediately yielded a marketable computer product. At the same time, their eventual applications connected research to industrial processes, engineering instrumentation and the management of complex infrastructure. This dual orientation between theory and application helps explain why cybernetics remained institutionally relevant even as the technical meaning of computing changed. The knowledge preserved in these fields later provided a basis for cooperation with informatics, statistics, artificial intelligence and advanced automation.

Programming also developed as a distinct body of professional knowledge as computers became increasingly involved in scientific, administrative and industrial work. A functioning machine required procedures capable of expressing problems in forms that could be executed and checked. Programmers needed to understand not only a formal language, but also the limitations of memory, input devices and computing time. Early software production was often inseparable from hardware maintenance and from the specialised requirements of a particular institution. Research laboratories used computation for mathematical and physical problems, while industrial users required reliable procedures for technical and organisational tasks. The accumulation of programming expertise therefore depended upon experience with real systems and the exchange of methods between institutions. Courses and professional seminars gradually

created opportunities to transmit those methods to younger specialists. The emergence of software as a recognisable technical activity was consequently an essential stage in the formation of computer science, even before private software enterprises became significant. By the end of the socialist period, Czechoslovakia possessed programmers and systems specialists whose skills could be redirected into new academic and commercial environments.

Industrial development introduced a different set of priorities from those governing academic computer research. State enterprises were expected to provide computing equipment and automation systems for production planning, technical administration and other institutional needs. The demand for large computers was connected with industrial management, scientific calculation and the information requirements of public organisations. During the 1960s and 1970s, domestic projects operated alongside the importation of foreign equipment and participation in technological programmes shared among socialist countries. The development of the Unified System of Electronic Computers reflected an attempt to create compatible computing capacity within the economic structures of the Eastern bloc. This approach promoted standardisation and cooperation, but also altered the possibilities for pursuing independent domestic hardware architectures. A government decision to prioritise common systems could influence the range of technologies available to engineers even when their laboratories had other promising ideas. The resulting landscape combined imported models, adapted designs, locally manufactured equipment and extensive effort devoted to keeping installed machines operational. Its practical achievements should not be dismissed, because functioning computing services required substantial expertise under demanding material conditions. Nevertheless, planned industrial allocation and international technological restrictions could delay equipment renewal and reduce the capacity to respond quickly to changing computing methods. These experiences shaped the technical knowledge and institutional expectations inherited by the Czech Republic in 1993.

The expansion of computing during the 1970s and 1980s gradually moved information processing beyond a small circle of pioneering laboratories. Large organisations employed computers for scientific calculations, industrial coordination, statistical reporting and the management of administrative records. Universities trained specialists in disciplines where algorithms, electronics and numerical methods became increasingly important. Computing centres also acquired responsibilities for supporting researchers who were not themselves computer specialists. Technicians and programmers worked with operating procedures shaped by particular machines, peripheral devices and restricted supplies of replacement components. The need to use scarce resources efficiently encouraged practical ingenuity, although it could also discourage experimentation with unfamiliar technological approaches. Where access to modern equipment was limited, theoretical training and simulation sometimes assumed greater relative importance. Thus, the professional knowledge of the late socialist period was both technically valuable and closely adapted to institutional circumstances that would change after 1989. The transition to a market economy would expose these specialists to different hardware standards, programming environments and forms of demand. It would also create opportunities to apply inherited expertise beyond the organisations for which it had originally been developed.

The spread of microprocessors and smaller computers made the final socialist decade qualitatively different from the era dominated by central computing installations. Eight-bit computers, educational machines and industrial controllers enlarged the range of settings in which programming could be encountered. Some devices were developed or assembled in Czechoslovakia, while foreign products and technical information circulated through channels of varying accessibility. Computing became more visible in technical schools, engineering workplaces and informal communities of enthusiasts. The history of these machines was not uniform across the Czech and Slovak parts of the federation, where different enterprises and educational networks possessed distinct roles. A history focused on the later Czech Republic must therefore avoid presenting every Czechoslovak product as the achievement of an institution located in the Czech lands. At the same time, the experience of using and programming small computers contributed to a generation of specialists capable of responding quickly to the personal-computer market after 1989. The shift towards individual access also changed expectations about the social purpose of computing, from a service delivered by a specialist centre to a tool used directly by an individual. It prepared the ground for software applications whose usefulness depended increasingly upon ordinary users rather than the internal requirements of a single large organisation.

The Academy computing infrastructure constituted another significant element of the national inheritance. The organisation now known as the Institute of Computer Science traces its origins to the computing centre established within the Czechoslovak Academy of Sciences in 1975. In its early period, the centre provided computing capacity and methodological assistance to scientists working in other disciplines. Such services were indispensable because many research groups lacked the equipment and specialist personnel required to conduct their own computer-intensive projects. The centre also contributed to the development of technical and programming methods and to the preservation of reusable scientific software. It became a scientific institute in 1980, illustrating the growing importance of computing as an object of research rather than merely a support service. During the 1980s, computation and information systems continued to serve practical scientific requirements within the Academy network. The organisation thus carried a dual identity combining infrastructure provision with the development of research expertise. After the political transition, the balance of its work increasingly shifted towards fundamental computer-science research. This transformation was gradual and cannot accurately be represented as the immediate disappearance of computing services on the first day of Czech independence. Its later evolution provides an especially clear institutional bridge between socialist scientific computing and the research priorities of the new republic.

Prague possessed several mutually reinforcing foundations for the development of computer science by the beginning of the 1990s. Charles University contributed mathematical training, research seminars and intellectual traditions in logic, algorithms and the formal treatment of information. The Czech Technical University in Prague supplied complementary expertise in electrical engineering, control systems, instrumentation and applied computation. Academy institutes created settings for specialised research in information theory, automation, mathematical methods and scientific computing. Professional cooperation across these environments could support research questions that no single department was equipped to

investigate alone. Their historical significance lay less in a fully unified Prague school than in a concentration of skills and institutions capable of sustaining distinct research communities. The relationship between university teaching and Academy-based investigation was especially important for preparing graduates to work on unfamiliar theoretical and technical problems. At the same time, centralisation of facilities and professional networks in the capital could create uneven access for researchers elsewhere in the country. The transformation after 1989 consequently opened possibilities for rethinking Prague's connections with regional universities and with international colleagues.

Brno developed its own computing traditions through the interaction of university mathematics, electronic engineering and industrial requirements. At Masaryk University, informatics-related education grew from mathematical disciplines before it acquired an independent faculty structure. At Brno University of Technology, a department specialising in automatic computers had been established within electrical engineering in 1964. Its subsequent development reflected the increasing importance of computer architecture, programming and applied information processing in technical education. These traditions were not simple copies of Prague's research environment because their institutional origins and practical emphases differed. They nevertheless shared the need to preserve rigorous mathematical and engineering education under rapidly changing technological circumstances. During the transition period, the growth of informatics encouraged universities to reconsider whether the subject should remain a specialisation inside older faculties. The later creation of a dedicated Faculty of Informatics at Masaryk University in 1994 was an outcome of discussions that had already advanced during 1993. At the technical university, the reorganisation of electrical engineering and computer science in 1993 likewise reflected the increasing weight of computation within professional training. Brno's subsequent international visibility rested partly on these older educational foundations rather than solely on the arrival of new digital companies.

Computing knowledge was also distributed among other Czechoslovak industrial centres, regional universities and specialised research organisations. Technical requirements in manufacturing, transport, electronics and public administration generated demand for mathematical programming and reliable information systems outside Prague and Brno. The distribution of expertise was nevertheless uneven because advanced equipment and specialised training depended upon institutional resources and administrative priorities. Not every workplace operating computers maintained an independent research programme, and not every technical graduate worked on original software or hardware design. These distinctions are necessary when reconstructing a national computer-science system from evidence of computer ownership or industrial activity. The Czech–Slovak federation also provided a shared professional space in which students, researchers and devices moved across an internal political boundary. After independence, many of these contacts continued, but they increasingly operated between institutions situated in separate states. A historically responsible account should therefore acknowledge shared Czechoslovak achievements without retrospectively attributing all of them to Czech research organisations. It should likewise recognise that regional scientific communities contributed capabilities that later became important to the country's more geographically diverse digital economy.

Mathematical logic and discrete mathematics supplied another foundation for Czech computer science that did not depend upon a particular generation of electronic machines. Questions concerning proof, formal languages, algorithms and finite structures could be investigated within mathematics departments and specialist seminars. Their relevance to computing became increasingly evident as software systems required precise specifications and algorithms for handling complex information. A formal result may provide the conceptual basis for new computational methods without immediately becoming a practical program or commercial product. For that reason, theoretical scholarship should not be assessed solely by the number of computers built or enterprises established around it. The coexistence of mathematical research and engineering education encouraged researchers to cross disciplinary boundaries while retaining distinct standards of evidence. Theoretical insights demanded proofs and conceptual arguments, whereas engineering systems also required testing under actual operating conditions. Both forms of knowledge became necessary as the discipline expanded towards information systems, software design and automated reasoning. This intellectual diversity was one of the resources available to the new Czech scientific system when institutional autonomy began to increase. Consequently, inherited competence in mathematical reasoning could retain its importance even as the available machines and institutional arrangements changed.

The socialist organisation of science shaped the direction of computer development in ways that cannot be reduced to a single judgement about success or failure. Central planning allowed governments to identify strategic technical priorities and maintain laboratories or educational programmes over long periods. It also placed decisions concerning investment, equipment supply and industrial production within administrative structures that were not necessarily responsive to researchers or users. Different ministries, institutes and enterprises could pursue objectives that were difficult to coordinate within an effective process of technological development. A prototype might therefore be scientifically promising while its industrial application remained delayed or abandoned. The system also separated many academic and industrial responsibilities, complicating the movement of new ideas from research laboratories into widespread use. Yet the same institutions accumulated knowledge, trained specialists and preserved equipment that could be indispensable to future scientific work. The historical question is consequently how particular organisational arrangements enabled some kinds of research while obstructing others. Judging the entire period solely through present-day commercial standards would obscure scientific work whose significance was primarily conceptual or educational. Equally, praising technically ingenious projects without examining their practical limitations would confuse laboratory potential with a sustainable computing industry. A balanced interpretation must account for both the achievements and the constraints that shaped the inherited Czechoslovak system.

Restrictions on access to advanced foreign components added a material dimension to these organisational problems. Domestic laboratories could design systems whose construction depended upon electronic devices, manufacturing processes or measurement instruments that were difficult to obtain. The pace of technological change abroad increased the difficulty because equipment could become dated before a locally designed system entered production. Industrial enterprises consequently faced pressures to adapt available technologies, import suitable

products or participate in standardised international programmes. These alternatives were not interchangeable, since purchasing a machine did not automatically create the capacity to design its architecture or maintain its software. Imported equipment also demanded trained personnel, documentation and procedures for adapting programs to local institutional needs. The results could include substantial practical expertise even where domestic hardware innovation remained limited. At the same time, restricted access to components and documentation could weaken the ability of researchers to test new approaches independently. The combination of ingenuity and technological dependence became an enduring feature of the late socialist computing environment. Its importance for the post-1989 transition lay in the contrast between strong human expertise and the increasingly visible need for modern, internationally compatible infrastructure.

Political conditions influenced the careers and opportunities of scientists as well as the technologies available to them. Academic appointments, foreign travel and institutional leadership were subject to forms of political oversight that differed markedly from standards associated with independent scholarly governance. The intellectual history of cybernetics reveals how ideological suspicion could temporarily narrow the range of acceptable research ideas. Later periods permitted greater recognition of mathematical and engineering work, although professional autonomy remained constrained. Research communities nevertheless preserved methods of argument, specialised publications and personal networks through changing political circumstances. Some of the most important forms of continuity were difficult to quantify, including doctoral supervision, technical judgement and the ability to formulate useful research questions. Such knowledge could survive even when institutional structures changed or major equipment became obsolete. The reforms after 1989 therefore released an existing community into a different professional environment rather than producing qualified computer scientists from nothing. Understanding that inherited human capital is essential for explaining how Czech institutions could respond relatively quickly to international opportunities during the 1990s.

The Velvet Revolution of November 1989 marked a deeper political and intellectual rupture than the subsequent constitutional division of Czechoslovakia. The end of communist rule enabled universities and research institutions to reconsider restrictions on academic freedom, governance and professional mobility. Researchers could engage with foreign colleagues under substantially different conditions and obtain information about rapidly evolving technologies with fewer political obstacles. Access to international publications and technical communities became increasingly important as global computing moved towards personal computers, open networks and software-intensive applications. Academic departments began adjusting their teaching and research priorities to demands that had not occupied the same position under the planned economy. The transformation was not an uncomplicated improvement in every respect because institutional budgets, employment conditions and organisational expectations also changed abruptly. Some inherited research groups faced uncertainty about their future, while others discovered new opportunities through foreign partnerships and growing market demand. The opening of the professional environment therefore generated simultaneous processes of intellectual liberation, organisational disruption and competitive adaptation. It also encouraged

recognition that expertise could be valuable beyond state enterprises, including within independent research teams and newly established businesses. The eventual computing system of the Czech Republic was shaped by this complex transition well before the independent state formally came into being. The difference between the political watershed of 1989 and the institutional watershed of 1993 is therefore central to the chronology of Czech information technology.

The transformation of the economy changed the conditions under which computer hardware and software could be produced, acquired and sold. State enterprises and research organisations confronted new forms of ownership, commercial competition and responsibility for their financial decisions. The growing availability of internationally produced personal computers made some established domestic hardware strategies commercially difficult to sustain. Importers, service providers and software developers increasingly responded to customer preferences rather than to allocations established through central industrial plans. Technical skills previously used within public organisations could support the creation of independent firms and specialised consultancy services. However, access to a market did not itself ensure that every research group could become a successful commercial enterprise. Developing products required management, finance, customer support, intellectual-property arrangements and the ability to maintain software across different systems. These requirements were especially challenging for professionals trained mainly to solve technical problems inside large institutions. The emergence of a private information technology sector therefore depended upon organisational learning as well as programming expertise. The early transition produced new possibilities for commercial innovation while exposing weaknesses in established industrial structures.

The expansion of international computer networking created an especially visible bridge between the final Czechoslovak years and independent Czechia. Academic institutions had begun exploring network communication before the federation dissolved, including participation in international university networking arrangements. Experimental internet connectivity preceded the formal ceremony held at the Czech Technical University in Prague on 13 February 1992. The connection linked the Czechoslovak academic community with a rapidly growing international environment for information exchange. Its early technical capacity was extremely modest by later standards, but its significance lay in establishing a functioning route for new kinds of scholarly communication. Researchers could increasingly envisage collaboration through shared digital messages and resources rather than exclusively through physical travel or printed correspondence. The practical development of networking required technical specialists capable of maintaining connections, coordinating institutions and establishing reliable services. The internet was therefore neither created by independence nor simply imported as a finished consumer product. Its arrival depended upon professional initiatives and institutional preparation that had already begun within Czechoslovakia.

In 1993, networking acquired a distinctly Czech national organisational dimension through the launch of the CESNET (Czech Educational and Scientific Network) academic backbone. The network began operating on 15 June and connected university locations through infrastructure that was limited in capacity but transformative in purpose. Its initial Prague–Brno backbone link operated at 64 kilobits per second, a modest figure that illustrates the technological conditions

of the period. The Czech Technical University in Prague initially operated the network, reflecting the role of established academic expertise in developing national connectivity. The network facilitated communication between institutions and supported their integration into an increasingly international research environment. It also demonstrated that shared digital infrastructure could become a collective national scientific resource rather than a service restricted to one laboratory. CESNET should not be confused with the association of the same name, which was established in 1996 and subsequently assumed responsibility for network operation. The distinction is important because a technological system and the legal organisation managing it may originate at different moments. In 1993, the immediate achievement was the construction and operation of a national academic network within the newly independent state. Its subsequent expansion would contribute to scientific cooperation and the wider development of Czech internet services. The network thus illustrates how institutional continuity from Czechoslovakia could become the basis for a new national digital infrastructure.

The reorganisation of the Academy of Sciences gave Czech computing research a new legal and administrative setting at the beginning of independence. The Czechoslovak Academy of Sciences ceased to exist at the end of 1992, while the Czech Academy of Sciences inherited much of its Czech institutional capacity. Act No 283/1992 provided a legislative basis for the successor organisation and its relationship with the state. Research institutes concerned with information theory, automatic control and computer science continued their work within this new framework. Continuity mattered because research programmes depended upon specialised libraries, laboratories, accumulated methods and experienced personnel. At the same time, the new Academy operated under changing expectations concerning scientific autonomy, external evaluation and international collaboration. Its institutes had to reconsider how their expertise fitted the priorities of an independent country and the competitive standards of international scholarship. The Institute of Computer Science exemplified this transition from an organisation historically associated with computing provision towards a stronger emphasis on scientific investigation. The Institute of Information Theory and Automation likewise preserved longer-standing research traditions while adapting to a different national governance structure. It also created a basis for more explicit cooperation among Academy institutes, universities and emerging industrial partners.

Changes in the financing of research reinforced this broader institutional transformation. The Czech Science Foundation was established in 1993 to support fundamental investigation through competitively assessed research projects. Such funding mechanisms encouraged scientists to formulate objectives, explain originality and seek resources through professional evaluation rather than administrative allocation alone. Computer science presented distinctive challenges within this model because fundamental theoretical work and expensive technical infrastructure could have very different financial requirements. A project in mathematical logic might depend mainly upon researchers and international exchange, while experimental computing could require costly equipment and technical staff. Competition also introduced uncertainty for groups accustomed to institutional planning, particularly where long-term expertise could not readily be expressed as short-term deliverables. Nevertheless, research grants provided opportunities for investigators to initiate projects and expand partnerships beyond inherited organisational

boundaries. The new arrangements did not eliminate the need for stable institutional support or the responsibilities of universities to educate successive generations of specialists. They instead changed the relationship between researcher initiative, public accountability and national scientific priorities.

Higher education was another arena in which the changes of 1993 had lasting consequences for computer science. Universities gained greater scope to reconsider academic organisation, research priorities and the place of informatics within established disciplines. Mathematical departments remained important because algorithms, logic and formal systems require rigorous conceptual training. Technical faculties provided expertise in computer engineering, electronic systems, industrial control and the implementation of software in real environments. However, the increasing breadth of informatics made the traditional allocation of computer-related subjects among existing faculties more difficult to maintain. The preparation of independent informatics programmes responded to the need for a professional identity that was neither exclusively mathematical nor merely electrical-engineering based. At Masaryk University, organisational initiatives launched in 1993 culminated in the foundation of the country's first dedicated Faculty of Informatics in 1994. Brno University of Technology reconfigured its faculty structure in 1993 to reflect the growing significance of computer science alongside electrical engineering. These developments should be interpreted as connected stages of an educational transformation rather than as events that all occurred on the first day of independence. They strengthened the institutional conditions for research-led teaching and the training of specialists for new scientific and commercial opportunities. The emerging university system thus combined inherited disciplinary depth with a more explicit recognition of informatics as a field in its own right.

The first private computer businesses emerged within a technological culture that already possessed local expertise in programming, electronics and applied mathematics. The development of anti-malware software provides one example of commercial activity whose origins reached into the late socialist period. Research on antivirus software that eventually led to the Avast enterprise began in 1988, before private technology business became a normal organisational form within the wider economy. The significance of such cases lies in demonstrating that the entrepreneurial transition was not uniformly initiated by the creation of the independent republic. It was accelerated by changes in market rules, computer ownership, foreign trade and the growing accessibility of internationally compatible software platforms. At the same time, early commercial survival depended upon the capacity to maintain programs, understand users and adapt products to competition beyond the national market. Commercial achievements should therefore be distinguished from the scientific discoveries or engineering methods upon which particular products might draw. The history of Czech software entrepreneurship is best understood as an interaction between accumulated technical competence and new market institutions. In 1993, these conditions were still emerging, and the internationally prominent Czech IT companies of later decades cannot be projected backwards as a fully developed national industry.

Evaluating the scientific inheritance of 1993 requires careful attention to the type and geographical location of each contribution. A machine designed at a research institute, a

computer manufactured by an industrial enterprise and a theoretical publication each represent different forms of achievement. The importance of an algorithm cannot be inferred from the number of units sold, just as the industrial significance of a computer cannot be established by technical originality alone. The distinction between Czech, Slovak and jointly Czechoslovak contributions also becomes essential when historical institutions are discussed retrospectively. Contemporary museum collections, institutional histories and specialist studies provide complementary evidence, but their emphases and levels of precision differ. Official institutional accounts are particularly useful for dates of foundation and organisational reform, whereas historical scholarship is needed to interpret technological and political causation. Retrospective descriptions of early computers should therefore be checked against evidence concerning design, operation and production rather than accepted as unqualified claims of priority. Such methodological discipline allows historical continuity to be recognised without assigning exclusive national ownership to internationally connected intellectual work. It also prevents the achievements of a few famous pioneers from obscuring the contributions of programmers, technicians, teachers and research administrators. The chapter accordingly privileges identifiable processes of knowledge formation, institutional adaptation and technical implementation over retrospective claims of uncomplicated national superiority.

By the beginning of 1993, the Czech Republic possessed neither an undeveloped computing culture nor a fully modern digital economy. It inherited important traditions in mathematical machines, cybernetics, information theory, control science, programming and scientific computation. Universities in Prague and Brno maintained educational and research communities whose expertise extended well beyond the lifespan of particular devices. Academy institutes preserved theoretical approaches, technical knowledge and professional relationships accumulated under very different political conditions. The late socialist period had also left constraints associated with industrial planning, technological dependence and restricted international scholarly movement. After 1989, openness to external ideas and market opportunities altered these conditions while exposing institutions and enterprises to considerable uncertainty. The independent state introduced a new framework for research governance, public finance and the organisation of national scientific infrastructure. The CESNET network provided an early example of how academic expertise could support a specifically Czech digital system while remaining internationally connected. Institutional and educational reforms likewise created opportunities for informatics to acquire a stronger identity within the national research environment. The resulting transition was neither a wholesale rejection of the Czechoslovak past nor a straightforward continuation of its economic and technological structures. It was the selective transformation of inherited capabilities under new rules of scientific cooperation, industrial competition and political responsibility. Understanding this watershed is the necessary starting point for examining the growth of Czech internet services, software enterprises and research infrastructures during the subsequent decades.

1993–2003: Post-Socialist Transformation, Personal Computing, the Emergence of the Internet and the First Czech Software Enterprises

The decade from 1993 to 2003 transformed computing in the Czech Republic from a specialised institutional resource into an increasingly ordinary instrument of work, communication and economic initiative. Its significance lies not in a single invention but in the interaction of technological availability, market reform and changing expectations about the uses of information. The newly independent republic inherited technically educated personnel and substantial computing experience from Czechoslovakia, yet the organisations employing that expertise were entering unfamiliar economic conditions. Large central computing installations remained useful for particular administrative and scientific tasks, while smaller machines gave individual organisations greater discretion over their own information systems. Imported equipment, commercial software and new communications services altered the practical meaning of participation in a computerised economy. Private entrepreneurs began to design applications, distribute hardware, maintain networks and offer services that would previously have been difficult to organise independently. Universities simultaneously expanded teaching and research in informatics, thereby contributing specialists to both public institutions and private companies. The Internet connected these developments by providing a common technological environment within which national and international activity could converge. Nevertheless, geographical inequalities, high access costs and limited purchasing power prevented digital technologies from spreading at a uniform pace. The history of this first post-Czechoslovak decade must therefore explain how inherited competence became a foundation for new markets without treating technological change as automatic or socially universal.

The conditions inherited in 1993 reflected several generations of Czechoslovak investment in mathematics, electronics, automation and data processing. Computing had been concentrated in universities, industrial enterprises, research institutes and specialised data-processing organisations, where access commonly depended upon institutional purpose and budgets. Professional operators, programmers and systems analysts had acquired expertise in maintaining equipment whose capabilities and interfaces differed greatly from contemporary personal computers. Some organisations possessed applications written for specific machines, and these applications embodied substantial knowledge of local administrative and production procedures. Such systems could not simply be abandoned without risking interruptions to accounting, logistics, technical calculation and scientific investigation. At the same time, dependence on older architectures created difficulties when suppliers, maintenance contracts and software standards changed. The emerging market demanded an assessment of whether existing systems should be retained, modified, interconnected or replaced with more widely supported platforms. Experienced computing personnel often became indispensable intermediaries between the technical past and the changing requirements of customers. This organisational knowledge was an asset in itself, even though its value rarely appeared in inventories of new equipment. Institutional continuity thus operated alongside technological substitution rather than disappearing under the influence of imported products. An adequate account of the decade must recognise this less visible labour of migration, maintenance and organisational adaptation.

The shift towards a market economy altered who could make decisions about computing and on what grounds those decisions were justified. Instead of relying primarily on administrative allocation, enterprises increasingly evaluated computers according to prices, expected productivity, available applications and maintenance costs. Ownership reform and the emergence of privately managed businesses created new customers for accounting packages, database services and computerised commercial records. Small firms could adopt computing without building the extensive data-processing departments characteristic of some large socialist organisations. Information technology became a purchasable combination of hardware, software, installation, training and continuing technical support. This commercial structure rewarded suppliers able to explain concrete benefits to customers unfamiliar with specialised computing terminology. Market competition also exposed weaknesses in organisations whose products depended upon protected procurement channels or inflexible institutional arrangements. Former state-sector specialists could enter private employment, establish firms or combine technical experience with new managerial responsibilities. Yet the transition was not a straightforward replacement of public knowledge by private enterprise, because educational institutions and research workplaces remained important sources of expertise. The distinctive development was a redistribution of initiative across organisations operating under increasingly varied economic and legal arrangements.

Personal computers increasingly changed the scale at which information could be created, stored and processed during the 1990s. A machine located on an individual desk offered access to word processing, spreadsheets, databases and elementary programming without requiring routine use of a central computer installation. For offices, this meant that the preparation of documents and calculation of business records could be organised closer to the employees responsible for them. For students and technically interested households, a personal computer provided a space for experimentation and self-directed learning. The growing presence of compatible personal-computer architectures encouraged the circulation of standard peripherals, replacement components and application software. However, acquisition costs remained substantial in relation to many household incomes, and equipment could become outdated quickly as technical specifications advanced. Organisations therefore had to balance the attractions of modern systems against the expense of replacement, staff training and data conversion. The spread of personal computing was shaped as much by purchasing decisions and practical support as by the capabilities of processors or memory. A household purchase and an enterprise investment therefore reflected different expectations of what the same technology was intended to achieve. It also influenced workplace organisation because responsibility for basic digital tasks became more widely distributed among employees. Personal computers consequently widened participation in information processing while creating new requirements for compatibility, maintenance and digital competence.

The commercial availability of computers depended upon distribution networks capable of connecting international manufacturers with Czech customers. Importers and resellers offered complete machines, components, printers, monitors and accessories, often alongside advice about suitable configurations. Some businesses assembled computers from internationally sourced parts and competed through service, flexibility and familiarity with local purchasing

conditions. Repair workshops and small technical firms became important because a malfunctioning computer could interrupt the routine operation of an office or shop. Suppliers also had to manage differences between new international standards and older equipment retained by their customers. A purchase could involve installation of an operating system, preparation of Czech-language settings, transfer of documents and instruction in everyday use. Hardware retailing therefore developed alongside a service economy in which knowledge and trust could matter as much as the machine itself. Trade events and specialist periodicals enabled customers to compare products and learn about rapidly changing configurations. These channels helped spread practical expertise beyond the relatively small groups that had encountered computers through university or industrial employment. They also demonstrated that an information-technology industry includes distribution and technical services even when the underlying hardware is manufactured abroad.

The software market evolved through a complex encounter between established local applications and products created for international operating environments. Text processing, financial administration and databases represented especially important requirements because they addressed recurrent tasks in almost every organisation. Increasing use of graphical user interfaces changed customer expectations about navigation, ease of learning and the presentation of information. Developers had to respond to hardware diversity and to successive versions of operating systems whose interfaces and file formats were not always compatible. Czech-language localisation introduced additional technical problems involving character encoding, keyboard layouts, fonts, spelling conventions and document interchange. Software that functioned satisfactorily in an English-language demonstration could still be unsuitable for a Czech office if diacritics were lost or printed documents were corrupted. These difficulties encouraged local programming and adaptation even where foreign applications dominated particular market segments. Commercial success required more than writing a functioning program, since distributors had to provide manuals, updates, customer assistance and reliable installation. The growing market for upgrades made long-term compatibility a commercial concern rather than a matter of technical elegance alone. The increasing significance of licensed software also required businesses to confront the economic and legal distinctions between copying a program and acquiring the right to use it. The result was a gradual professionalisation of software provision, with technical quality becoming inseparable from support and commercial organisation.

The history of Software602 illustrates how locally developed office applications could preserve relevance during the transition to personal computing. The text editor T602 had become widely associated with word processing in the late Czechoslovak period, when suitable Czech-language software was comparatively difficult to obtain. Its significance extended beyond a particular program because it helped users understand the computer as a practical tool for routine correspondence and document preparation. After the political transition, the company developed within an environment in which demand for office software was expanding but international competitors were becoming increasingly accessible. The movement towards graphical operating systems and networked document exchange obliged suppliers to reconsider familiar application designs. Customers wanted to retain existing documents while acquiring

capabilities compatible with newer hardware and organisational procedures. A locally recognisable product could enjoy advantages of familiarity and linguistic adaptation, yet these advantages did not remove pressure to innovate. Software602's early experience therefore illuminates the relation between continuity in software use and discontinuity in commercial and technical circumstances. It also shows why a national software industry cannot be evaluated solely through internationally famous products, since domestic office applications can shape digital adoption across thousands of routine tasks. The broader historical issue concerns how users and developers negotiated transitions between generations of software without losing accumulated information.

The establishment of Zoner in Brno in 1993 offers a complementary example of new commercial software development oriented towards accessible visual tools. The company identifies Zoner Callisto and Zebra as early vector-graphics products, placing graphical communication among its initial areas of specialisation. Such applications served users creating illustrations, diagrams, printed materials and other visual documents without relying entirely upon expensive professional production systems. Graphic software required programmers to combine mathematical representations of shapes with interfaces that non-specialists could learn to operate. The technical problem therefore differed from that of a conventional text editor, even though both belonged to the expanding market for personal-computer applications. Zoner developed Media Explorer during 1994, anticipating a growing requirement to organise and work with digital visual files. The opening of an American branch in 1999 indicated that a Czech software enterprise could attempt direct participation in overseas markets during the first decade of independence. Internationalisation nevertheless demanded adaptation to foreign customers, distribution channels and forms of technical support. The Czech origins of the company remained analytically distinct from the later geographical reach of its customers and business operations. The company's trajectory demonstrates the possibility of turning a specific software competence into a gradually diversified commercial organisation. Its history also cautions against portraying the entire sector as having developed only through security software or internet portals.

Computer trade fairs and professional media helped translate unfamiliar technologies into products that business managers and ordinary consumers could assess. The Invex-Computer exhibition introduced in Brno in 1991 became an important meeting place for hardware suppliers, software developers, journalists and potential customers. Its emergence reflected a wider reorganisation of exhibition activity as the Czech economy moved towards a more competitive commercial environment. Demonstrations could bring together desktop machines, network equipment, printers and applications that would otherwise be encountered through disconnected sales channels. Public comparison of products encouraged suppliers to explain new capabilities in practical rather than exclusively engineering terms. Specialist magazines and technical books similarly offered instructions, product evaluations and discussion of emerging computer standards. Training providers found opportunities in the growing demand for employees who could use office software and maintain basic local networks. Such institutions helped form a recognisable professional community extending beyond researchers and experienced programmers. They also contributed to the diffusion of technical terminology in Czech, a necessary condition for communicating complex developments to new audiences. The

economic importance of these channels lay in their ability to connect the supply of computing technology with the knowledge required to use it competently.

The transition to networked computing introduced possibilities that individual desktop machines could not provide independently. Local area networks enabled offices to share printers, exchange files and coordinate access to information stored on central servers. Network administrators became responsible for access permissions, backups, fault diagnosis and the compatibility of different computing environments. Commercial customers increasingly recognised that installing several computers was not equivalent to building a reliable information system. Networking projects involved cabling, equipment selection, software configuration and decisions about the organisation of data across departments. The growing use of electronic communication changed the expected speed of internal coordination, although many organisations retained paper-based procedures. Scientific institutions were particularly receptive to network technologies because research depended upon exchange of data, specialist software and collaboration across institutions. However, wider adoption required suitable telecommunications infrastructure and expertise that was not evenly available across the country. Electronic mail, although technically simple by subsequent standards, became one of the first services capable of demonstrating the everyday utility of interconnection. Networked computing therefore represented an organisational innovation as well as a technical change in the way machines communicated. It helped prepare Czech organisations for the much more extensive transformation associated with public Internet access.

The Czech Internet did not begin with the appearance of commercial websites in the middle of the 1990s. Czechoslovak researchers had already participated in international academic networking, and the formal connection to the Internet was marked on 13 February 1992 at the Czech Technical University in Prague. This event preceded the establishment of the independent republic and must therefore be treated as part of the inherited national infrastructure. Initial connections were designed primarily for educational and scientific communication rather than for a mass consumer market. Technical specialists had to manage leased circuits, network configuration, international links and the practical difficulties of scarce bandwidth. Electronic mail and access to remote information offered research communities opportunities that were not dependent upon exchanging physical media. The influence of these facilities extended beyond convenience because faster scholarly communication could transform how projects were coordinated and information obtained. Nevertheless, the first institutional users should not be confused with the population as a whole, which generally lacked affordable equipment or network subscriptions. The early Internet was therefore a setting for specialist cooperation whose eventual commercial significance was not yet fully established. This background explains why universities and technical experts played an unusually prominent part in the first stages of Czech Internet development.

The nationwide academic backbone known as CESNET (Czech Educational and Scientific Network) was launched on 15 June 1993, giving the new republic a practical network infrastructure of its own. The Czech Technical University in Prague initially operated the system, which linked major educational centres across the country. Its principal Prague–Brno connection used a fixed line with a capacity of 64 kilobits per second, a figure that illustrates the modest

bandwidth available at the time. The achievement was important not because it approached contemporary performance but because it provided an organised framework for inter-university exchange. The network connected separate institutions through common communication arrangements rather than requiring each workplace to improvise isolated international connections. Network engineers were obliged to address routing, capacity allocation, operational reliability and expansion into additional university towns. Academic cooperation thus created technical assets and practical expertise that could later support a broader information society. The early network also supplied a basis for developing professional relationships among administrators, universities and international partners. This initial capacity should be interpreted in relation to the early 1990s rather than judged against the much more demanding networks of later decades. Its creation demonstrates how public investment in research infrastructure could produce benefits extending beyond the immediate requirements of individual scientific projects. The establishment of CESNET was consequently one of the clearest institutional landmarks in the transformation of Czech information technology after independence.

The expansion of academic connectivity into regional university cities gradually altered the geography of computing opportunities. Connections developed beyond Prague and Brno, including university centres such as Plzeň, Liberec, České Budějovice, Olomouc and Ostrava. This distribution mattered because access to external information had previously been strongly influenced by the location and resources of individual institutions. A connected faculty could participate more readily in international correspondence, exchange software and obtain scientific materials from remote repositories. Students gained an environment in which learning about network protocols could be joined to practical experience with functioning infrastructure. Technical personnel at regional institutions also acquired expertise in operating services that would soon become relevant to commercial customers. The establishment of the CESNET association in 1996 transferred network operation from the Czech Technical University to a wider organisational framework representing participating institutions. This arrangement supported longer-term planning while maintaining the network's identity as a resource for education and research. Regional networking did not immediately eliminate disparities in access, since capacity, equipment and institutional resources continued to differ. Nevertheless, it made the emerging digital research environment less exclusively dependent upon facilities concentrated in the capital.

Commercial access to the Internet developed progressively rather than appearing fully formed after the establishment of Czech independence. CESNET's history identifies 1994 as the year in which the first commercial Internet providers appeared in the Czech Republic. Initially, commercial connectivity remained closely associated with the academic backbone and with a limited telecommunications environment. The development of a broader market required providers to obtain network capacity, establish technical operations and offer contractual services to customers outside universities. The regulatory conditions of public data services were evolving, and historians of the Czech Internet distinguish early exceptional arrangements from wider liberalisation during 1995. Providers such as EUnet and other emerging operators helped create alternatives through which businesses could connect to international information networks. Commercial subscriptions involved charges that could be substantial for a small

enterprise, especially when additional telephone or leased-line expenses were considered. Internet services were consequently first adopted most readily by organisations able to justify them through professional or commercial use. A technically available connection could thus remain economically inaccessible, particularly to households and very small organisations. The existence of competing operators nevertheless changed the institutional character of networking by making connectivity an identifiable market service. This shift laid the foundations for later expansion without making the mid-1990s Internet universally affordable or technically simple.

The cost of telecommunications became a persistent constraint upon the growth of residential Internet use. For many households, accessing the network required an analogue modem and a telephone call billed according to connection duration. Even when an Internet provider offered an apparently modest subscription, the combined price of connectivity and telephone use could discourage extended sessions. Connection speeds limited the practical enjoyment of graphical websites and made the transfer of large files especially slow. Users often prepared messages while disconnected and then went online briefly to reduce their expenses. The controversy surrounding announced increases in telephone charges in 1998 made these limitations a subject of public debate. The protest movement known as Internet proti monopolu, or Internet Against Monopoly, showed that network access had become a social and regulatory question rather than a concern of technical specialists alone. The subsequent introduction of a special tariff for Internet calls in 1999 provided some relief without removing the structural limitations of dial-up access. Telecommunications policy therefore influenced how rapidly households could participate in digital communication and information services. The struggle over access costs was an important reminder that the Internet's economic and social consequences depended upon the conditions under which it could actually be used.

The growing number of independent networks created the need for arrangements through which traffic could be exchanged efficiently inside the Czech Republic. NIX.CZ, a neutral Internet exchange organisation, was founded in 1996 by participants from the emerging telecommunications and Internet market. Its underlying function was to provide a setting in which separate networks could interconnect without routing all relevant traffic through inefficient external paths. The benefits of domestic exchange included improved operational coordination and opportunities to reduce some costs associated with interconnection. Participation required cooperation among companies that might simultaneously compete for the same business customers. Such an arrangement shows how market rivalry and collective infrastructure building can coexist within a developing technology sector. The exchange point also depended on specialised technical knowledge concerning routers, network management and the reliable transmission of data. The association's emergence was therefore an organisational innovation as well as an investment in physical connectivity. Neutral interconnection reduced one particular obstacle to market development, although it could not solve every difficulty associated with national telecommunications. It made the structure of the Czech Internet less dependent upon a single academic operator and more reflective of a diversified provider market. By the end of the decade, this kind of shared infrastructure had become an important precondition for the further expansion of national Internet services.

The new Czech national Internet identity was also expressed through the development of domain-name administration. Following the dissolution of Czechoslovakia, the country-code domain .cz was introduced in January 1993, replacing the earlier federal context of .cs. Domain names supplied a recognisable addressing framework through which universities, companies and individuals could establish a public online presence. As registrations increased, the administration of this resource became too important to rely indefinitely upon arrangements developed for a small technical community. The association CZ.NIC was founded on 21 May 1998 as a cooperative institutional response to the requirements of domain-name management. In September 1999 it formally assumed responsibility for administering the national domain, according to the association's documented history. This transition involved questions of registration policy, operational reliability, institutional neutrality and the division of responsibilities among providers. The domain registry was not a software company in the ordinary commercial sense, yet its dependable operation was essential to the functioning of innumerable private and public websites. It demonstrates how an emerging digital economy requires collectively maintained administrative systems in addition to entrepreneurs offering end-user products. The development of the .cz domain thus marked both the emergence of a distinctive national online space and the professionalisation of its technical governance.

The appearance of Czech-language Internet portals made online information increasingly accessible to users outside professional computing circles. Seznam.cz was launched by Ivo Lukačovič in April 1996 as a directory organised around categories of websites and practical routes towards available information. According to the company's historical account, its initial investment was 50,000 Czech crowns, illustrating the comparatively modest resources from which some digital ventures began. The early project addressed a genuine problem of discovery, because a growing Internet was difficult to navigate without useful directories and search functions. The company's development depended upon understanding Czech users, maintaining a usable collection of links and making the service sufficiently familiar to encourage return visits. Seznam introduced its own full-text search function during 1997, extending the possibilities of finding information beyond browsing manually arranged categories. The treatment of Czech diacritics was particularly significant because search technologies designed for other languages did not always handle national spelling reliably. An Internet portal therefore required technical adaptation to linguistic conditions as well as a commercially attractive interface. The portal gave advertisers a reason to finance local digital services, although commercialisation did not guarantee the quality of every item presented to users. Seznam became a representative example of domestic innovation built upon the particular requirements of the Czech online market. Its early success demonstrates that a locally focused digital enterprise could compete through relevance and service integration rather than through ownership of the world's largest technological infrastructure.

The rapid expansion of portal services showed how the Internet was becoming a medium for communication and information consumption. Seznam added a free electronic-mail service in 1998, helping to make a personal online identity available to people who did not work within universities or large enterprises. Other services developed around directories, communities, news and electronic shopping, gradually increasing the time users could spend within Czech-

language online environments. Each additional function created technical requirements involving accounts, servers, databases, reliability and the protection of stored information. The business models of portals also evolved, with online advertising offering a way to finance services that were free to many individual users. The growth of user traffic encouraged publishers to reconsider how audiences might be reached outside printed newspapers or conventional broadcasting. Nevertheless, early online readership and advertisement revenues should not be projected backwards from the much larger markets of later decades. Portals operated in an environment of limited household connectivity, uneven user experience and considerable uncertainty about commercially sustainable Internet services. Their significance lay in creating practical reasons for people to go online and in demonstrating that useful Czech-language information services could form a business. The transformation from a directory to a range of integrated services was consequently a central feature of the emerging domestic web economy.

Commercial websites also changed the relation between Czech enterprises and their customers. An online presence allowed a company to publish product information, opening hours, contact details and catalogues without relying entirely upon printed publicity. For some businesses, electronic mail became an alternative to telephone calls and physical correspondence when responding to enquiries or coordinating deliveries. Early experiments in electronic commerce introduced questions about ordering, payment, consumer confidence and the fulfilment of transactions. The technical availability of a website did not automatically establish a viable online business, especially when many customers remained reluctant to transmit financial information electronically. Developers needed to design interfaces that were understandable, secure and suitable for the organisation's practical procedures. Banks, retailers and service providers approached these problems with different resources and different expectations of operational risk. Commercial adoption also raised legal questions concerning contracts, intellectual property, protection of customer information and the status of electronic records. A company brochure transferred to the web was therefore only the beginning of a more demanding process of digital business transformation. These challenges encouraged connections between programmers, managers, lawyers and specialists in information security. The first generation of Czech commercial websites should therefore be interpreted as experiments in organisational change rather than as simple reproductions of conventional shops on a screen.

The expansion of the Czech web created opportunities for enterprises offering hosting, domain registration and related technical services. Small organisations frequently lacked the skills or resources necessary to operate their own publicly accessible servers on a continuous basis. Commercial hosting companies provided an alternative by combining physical equipment, network connectivity, administration and customer assistance. Zoner's history records the development of its CZECHIA.COM hosting activity in 1996, illustrating how a software company could diversify into network services. Such firms performed work that remained largely invisible to the ordinary user, including system updates, management of storage and responses to technical incidents. The relationship between a web designer and a hosting provider also encouraged specialisation within the expanding digital-services market. Domain registration introduced recurring administrative tasks that differed from the original installation of a customer website. As clients grew more sophisticated, providers faced demands for reliability, security and

support for database-backed or interactive applications. The growth of hosting services demonstrated that the national Internet economy required layers of technical intermediaries, not merely prominent consumer websites. It also opened entrepreneurial opportunities to firms capable of providing consistent service without producing original computer hardware.

The emergence of antivirus software as a Czech commercial specialisation had roots preceding the political changes of 1989. Pavel Baudiš encountered malicious software while working in the Prague research environment and developed an early program for its removal in 1988. His cooperation with Eduard Kučera subsequently provided the foundation for the Alwil software business, which was formally established in 1991. This sequence illustrates how technical knowledge accumulated within an earlier institutional system could be transformed into a private enterprise under new political conditions. The growing use of personal computers created a market for protection against malicious programs transmitted through removable media and later through networked communication. Antivirus development required close observation of threats, reliable updating of detection methods and the ability to make protective software usable by non-specialists. The significance of these technical tasks should not be reduced to the eventual international reputation of a single brand. They demanded sustained programming, testing and customer support while the computing environment underwent rapid change. The development of regularly updated security software also exposed weaknesses in business models dependent solely upon infrequent physical distribution. The early Alwil experience therefore combined continuity in technical competence with a genuinely new opportunity to market a specialised product internationally. It helped establish information security as one of the most distinctive commercial directions of Czech software development.

The commercial approach associated with Avast changed during the later years of the period as the distribution of software increasingly interacted with the Internet. In June 2001 Alwil introduced a free antivirus solution for non-commercial home use, according to the company's published historical account. The model reflected an attempt to enlarge protection among private users while developing a much broader community around the product. A free household licence was not the same as unrestricted open-source software, since the company retained control over its proprietary technology and licensing terms. The commercial logic relied upon distinguishing user groups and finding ways to support software development beyond payment by every individual household. Network distribution made it easier to communicate with users and circulate updates than had been possible through physical disks alone. At the same time, software security became more demanding as the number of connected machines and the variety of malicious programs increased. The strategy illustrates how an innovation can concern a distribution or licensing model as well as the underlying detection technology. It also shows that commercial expansion need not begin with expensive mass-market hardware or a large domestic customer base. The development of this approach helped prepare the firm for subsequent international growth, although its later scale lies beyond the period examined in this chapter.

Brno developed another important antivirus enterprise through Grisoft, founded in 1991 by Jan Gritzbach and Tomáš Hofer. The company combined early computer-related commercial activity with development and distribution of its own security software. Its subsequent products became associated with the AVG name, which would later acquire much wider international recognition.

The company emerged from the same general transition towards private software enterprise as Alwil but followed a different organisational and commercial path. The coexistence of these businesses indicates that Czech expertise in protection against malicious software was not limited to a single research team or city. Antivirus products required specialisation in examining program behaviour, identifying threats and supporting customers whose technical knowledge varied widely. As computers became networked, the stakes of ineffective protection extended from individual files to the continuity of organisational operations. International distribution also demanded attention to language, technical support and the reliability of updates delivered across borders. The growing association between Czech programmers and reliable antivirus protection reflected identifiable enterprises rather than a formally unified national research programme. It would be historically misleading to read later acquisitions and brand changes back into the company's independent early-1990s identity. The essential achievement of the first decade was the creation of commercially sustainable security-software expertise with possibilities for international expansion.

International technology companies influenced Czech computing both through the sale of products and through the organisation of their local activities. The presence of foreign hardware and software suppliers enlarged access to internationally established platforms, documentation and professional methods. Microsoft's recorded establishment of a Czech subsidiary in 1992 exemplifies the way major software firms entered the market during the broader political transition. Foreign vendors often relied on local partners for distribution, installation, service and the adaptation of products to Czech requirements. Their operations could stimulate demand for certified specialists, professional training and internationally recognisable technical qualifications. Competition with global products simultaneously placed pressure on domestic developers to identify particular strengths rather than reproduce every general-purpose application. Some Czech enterprises benefited by integrating imported tools into systems adapted to local organisational requirements. Others sought opportunities in original software development, specialised technical services or export markets where national scale mattered less. The implications of international investment therefore cannot be summarised as either technological dependence or an unqualified transfer of prosperity. It created new capabilities and commercial relationships while also exposing domestic companies to stronger competitive pressures and changes in ownership structures.

The earliest Czech digital ventures also demonstrated that software engineering could support creative industries and exportable cultural products. Bohemia Interactive was established in 1999, drawing on a small development team working with sophisticated interactive simulation and computer graphics. Its internationally successful game Operation Flashpoint appeared in 2001 and required capabilities extending beyond routine application programming. The development of a complex game involved rendering, modelling, software architecture, simulated environments and the organisation of creative teams. This achievement was notable because a digitally delivered product could reach an international audience without large-scale domestic manufacturing facilities. International publishers and distribution relationships nevertheless remained important in bringing the product to wider markets. The technical knowledge generated in game development intersected with broader competencies in visualisation, interactive

systems and software testing. At the same time, game production posed distinctive challenges involving artistic judgement, storytelling, user experience and commercial risk. Commercial games also required the coordination of multidisciplinary labour, including developers, artists, designers and external publishing partners. Its inclusion in the history of information technology therefore expands the definition of the industry without confusing creative success with a fundamental computer-science discovery. By 2003, this example showed that Czech programmers could participate in world markets across a wider range of software categories than office applications or information security.

The expansion of an independent IT industry increased the importance of specialist education and the renewal of university programmes. Masaryk University established its Faculty of Informatics in September 1994 as the first independent faculty of its kind in the Czech Republic. The faculty developed from earlier teaching within the Faculty of Science and responded to the growing academic and practical significance of informatics. Its creation was an institutional recognition that computer science required sustained intellectual development rather than treatment solely as an auxiliary skill. The new faculty combined mathematical and theoretical study with fields increasingly relevant to the emerging digital economy. Its early existence demonstrated the importance of Brno as a centre for specialist training, alongside Prague's established technical and academic institutions. Universities faced the task of teaching enduring concepts while updating equipment and courses to reflect rapidly changing software and network technologies. The distinction between preparing researchers and preparing competent practitioners did not imply that the two purposes were mutually exclusive. Graduates trained in algorithms, programming and systems analysis could contribute to private enterprise without abandoning the principles of rigorous scientific reasoning. The professionalisation of higher education therefore provided a durable institutional foundation for market growth beyond the enthusiasm of individual entrepreneurs.

Other educational developments reflected the growing need to combine computer science with the reliable management of complex organisations. Masaryk University introduced its university information system in 1999, making electronic study administration an important element of institutional operation. The project illustrated how a university could serve simultaneously as a place for teaching informatics and as a demanding user of modern information systems. The Faculty of Information Technology at Brno University of Technology was established in 2002, adding another specialised organisational setting for advanced computing education. Technical universities in Prague and elsewhere also adapted programmes that connected programming with electronics, telecommunications, applied mathematics and engineering. Students increasingly needed experience of networks, software projects, system maintenance and collaboration in addition to individual coding exercises. Professional learning continued outside universities through vendor courses, workplace instruction and technical communities organised around practical problems. The growth of these educational routes reflected a labour market with varied requirements, from basic computer support to original software design. The Faculty of Informatics at Masaryk University and the newer faculty in Brno thus represented complementary responses to demands that had grown rapidly during the 1990s. Nevertheless, education could not respond instantaneously to every new technological fashion, and graduates

still depended upon opportunities for continuing professional development. The lasting significance of the period was the integration of digital expertise into broader systems of formal education and workplace learning.

The social distribution of digital technologies remained uneven at the end of the first post-Czechoslovak decade. Statistical evidence from the Czech Statistical Office indicates that personal-computer ownership and household Internet access were still far from universal in 2003. Differences in income, educational attainment, household composition and place of residence affected the opportunities available to potential users. Schools and public institutions therefore had an important role in providing experiences of digital technology that were not always available at home. The expansion of commercial services did not by itself resolve affordability or the limitations of local telecommunications infrastructure. Some firms acquired computers chiefly for accounting or document production while remaining hesitant about extensive electronic commerce. Others integrated networks more deeply into their operations and became early participants in digital forms of organisation. These contrasting patterns warn against portraying the emergence of an Internet economy as the disappearance of traditional business practices. The transition also created new forms of exclusion when administrative or commercial services increasingly assumed that citizens possessed equipment and technical competence. Digital development was thus a process of social differentiation as well as an expansion of technological possibilities.

By 2003, the Czech Republic possessed a more diversified computing economy than the one inherited from Czechoslovakia a decade earlier. Academic networking had developed into a national infrastructure accompanied by commercial Internet providers, exchange arrangements and organised domain administration. Personal computers and standard applications had become increasingly common in professional life, even though household access remained socially and geographically unequal. Private firms were producing Czech-language software, hosting websites, developing information-security technologies and reaching users outside the national market. The early history of Seznam, Zoner, Alwil, Grisoft and Bohemia Interactive demonstrated several distinct models of technological entrepreneurship rather than a single national development path. Foreign suppliers contributed platforms and market connections, while universities expanded education and helped preserve the intellectual foundations of informatics. None of these changes meant that Czech computer science had been reduced to commerce or that public research had ceased to matter. The decisive transformation was the creation of new relationships among research institutions, technical services, software developers, telecommunications operators and everyday users. The historical importance of the decade lies in this combination of organisational pluralism, intellectual continuity and new technological opportunities. These relationships established conditions for subsequent European integration and the further development of digital infrastructure after 2004. The years 1993–2003 should therefore be understood as a formative period in which technological inheritance was reorganised into a complex and increasingly internationally connected information-technology ecosystem.

2004–2010: European Integration, the Expansion of Digital Infrastructure and the Consolidation of Czech Information Technologies

The years from 2004 to 2010 marked a transition in which Czech information technology became more extensively connected to European institutions, markets and research infrastructures. Accession to the European Union (EU) on 1 May 2004 changed the regulatory and financial environment without suddenly replacing the technical capabilities accumulated during the preceding decade. Universities entered this stage with established informatics departments, experienced programmers and growing participation in international scientific networks. Private enterprises already served domestic customers through software development, technical support, internet portals and electronic communication services. The principal historical change concerned the scale on which these activities could be coordinated, financed and compared with developments elsewhere in Europe. Broadband networks began to alter household behaviour, while institutional connections made increasingly demanding scientific collaboration possible. Government agencies gradually moved from publishing information online towards redesigning the processes through which administrative documents could be requested, transmitted and authenticated. At the same time, international investment and competition placed Czech software businesses within commercial networks extending beyond the country's relatively small home market. The period consequently requires analysis of infrastructures, skills and institutions as well as of individual companies or technological products. Its historical significance lies in the consolidation of several previously separate aspects of computing into a more interconnected national digital environment.

The republic did not enter the European Union as a technological blank slate, and the distinction between inheritance and new development is essential to this account. During the 1990s, the distribution of personal computers had changed workplace routines and brought networked communication into schools, offices and an increasing number of homes. The national research network CESNET (Czech Education and Scientific Network) had already connected universities to international scientific communication, while private internet providers established commercial access outside the academic sector. Software enterprises had developed experience in localisation, database systems, computer protection and applications for domestic organisations. These earlier developments gave Czech actors practical skills that could be used when European markets became more accessible and regulatory expectations changed. Nevertheless, access to hardware did not guarantee efficient information management, because organisations also needed reliable connections, trained employees and compatible administrative procedures. A small business using electronic mail faced different technical and commercial requirements from a university laboratory transmitting large scientific datasets. Municipal offices likewise had to reconcile electronic documents with legal standards devised for paper-based administration. The period after accession therefore produced uneven adjustments rather than a single universal process of technological modernisation. To explain its achievements, it is necessary to follow the ways in which different sectors built upon inherited competence while confronting new institutional obligations. The continuity of people and organisations was as important as the novelty of particular technical systems.

European integration introduced a policy framework linking information technologies to competitiveness, research cooperation and the circulation of knowledge. The Lisbon Strategy had already established a European ambition to strengthen a knowledge-based economy, and Czech public policy increasingly operated within this shared language. Membership improved access to Union decision-making and to financial programmes while imposing obligations associated with the common market and its regulatory rules. It would be misleading, however, to attribute the beginning of international research participation to accession alone. Czech organisations had already taken part in European framework programmes and scientific exchanges before May 2004, including arrangements that enabled cooperation with foreign universities. The Sixth Framework Programme for Research and Technological Development covered 2002–2006, crossing the boundary between the pre-accession and membership periods. Its successor, the Seventh Framework Programme, began in 2007 and provided a longer institutional horizon for collaborative research through 2013. Research groups could therefore pursue relationships initiated before accession while preparing new proposals within expanding European networks. The resulting opportunities were accompanied by competition, requirements for project administration and the need to demonstrate the quality of proposed contributions. European integration should thus be understood as an enlargement of possibilities rather than as an automatic explanation for every Czech technological achievement.

The alignment of electronic communications rules with European legislation changed the operating environment for telecommunications providers and their customers. A functioning digital economy depended on more than the presence of cables, transmitters and internet access points, because competitive markets also required transparent rights and obligations. The Czech Electronic Communications Act, Act No. 127/2005 of the Czech Collection of Laws, established a central legal framework for electronic communication services during this stage. Its significance included the regulation of market relationships, network access and the responsibilities of providers within an increasingly liberalised European environment. Regulatory development had to address the continuing influence of established network operators alongside the commercial interests of alternative service providers. Competition could encourage investment and differentiated services, but its practical effects varied according to local infrastructure, customer density and access to capital. For households, technical availability was only one determinant of internet adoption, since subscription charges and equipment costs also influenced decisions. For enterprises, greater choice of communications services could make remote collaboration and distributed information systems more feasible. A historical assessment therefore needs to distinguish formal market liberalisation from actual improvements in connectivity experienced by particular users. The interpretation of regulatory reform also requires separating the intentions expressed in legislation from subsequent enforcement and market behaviour. The legal architecture of the period provided necessary conditions for development without guaranteeing identical outcomes across the country.

Telecommunications modernisation involved competition among technologies that offered different trade-offs in speed, geographic coverage and installation costs. Digital subscriber line connections made use of existing telephone infrastructure, while cable television networks supplied another path towards relatively stable household broadband. Local wireless providers

developed services particularly relevant to settlements where extensive fixed-line upgrades were expensive or commercially unattractive. The historical importance of these alternatives can be seen in the unusually strong Czech reliance on wireless connections compared with many other European countries. An operator serving a smaller municipality could sometimes create a viable service by combining shared upstream access with locally installed radio links. Such an arrangement might widen availability, although weather, interference, capacity sharing and maintenance still influenced connection quality. Urban customers generally encountered a broader choice of providers and technical platforms than households in sparsely populated areas. Businesses likewise evaluated connectivity in relation to reliability, contractual support and the demands of particular applications rather than advertised download speeds alone. The expansion of broadband was therefore neither technologically uniform nor reducible to the replacement of one transmission medium by another. It represented a decentralised process in which regulatory change, local entrepreneurship and infrastructural limitations interacted.

Historical statistical evidence demonstrates the magnitude of the household broadband transition more clearly than general claims about widespread digitalisation. The Czech Statistical Office recorded broadband connections in 5.1 per cent of households in 2005, using the survey definitions applied in that statistical series. The corresponding share rose to 15.1 per cent in 2006 and 25.6 per cent in 2007, illustrating rapid adoption from a comparatively modest base. By 2008, the proportion had reached 33.1 per cent, and it increased further to 44.4 per cent in 2009. The reported figure for 2010 was 50.9 per cent of households, representing a substantial change within only five years. These values should not be confused with the percentage of households that possessed any form of internet connection, since the indicators measure different categories. They also refer to survey populations and definitions that must be considered when comparing national and European datasets. The increase created new practical opportunities for remote services, electronic correspondence, digital media and internet-based transactions. Nevertheless, a national average concealed differences associated with age, education, income and the settlement in which a household was located. The statistical record consequently demonstrates both the speed of expansion and the need for caution when describing digital connectivity as universally accessible. A broader networked society was emerging, but its benefits remained socially and geographically uneven.

The transition from dial-up communication to broadband altered not merely the speed but also the ordinary temporal organisation of internet use. A connection that required a separate telephone call encouraged short sessions and made household expenditure more directly sensitive to time spent online. More persistent broadband access allowed users to exchange files, browse information and maintain electronic communication with less interruption. According to the Czech Statistical Office, telephone-line dial-up still represented a substantial part of household connectivity in 2006, whereas high-speed access predominated among connected households by 2010. The same statistical account reported that Wi-Fi connections were especially common and were used by nearly one million households during the second quarter of 2010. This development gave users greater freedom to explore services that had previously been impractical over slow or expensive links. Online banking, product comparison, digital photographs and interactive websites became more credible elements of everyday

behaviour. The growing regularity of access also changed expectations about customer support, online information and the accessibility of organisations through the web. However, reliable use still depended on the quality of domestic equipment, the stability of service provision and the ability to identify unsafe content. Broadband expansion should therefore be understood as a transformation of user practices rather than a simple numerical increase in network capacity.

Digital participation grew especially rapidly among students and younger adults, but the expansion was uneven across demographic groups. The Czech Statistical Office reported that approximately 62 per cent of people aged sixteen and over used the internet in 2010. Younger people were much more likely to participate than older cohorts, while educational attainment remained associated with differences in use. This distribution mattered because internet services increasingly influenced how people searched for employment, acquired information and communicated with institutions. Household access also affected the practical benefits available to pupils and students outside educational establishments. A person without a suitable computer or reliable connection could be excluded from activities that other users increasingly treated as routine. Internet literacy consequently involved more than the ability to operate a browser, extending to searching, evaluating information and protecting personal data. Public libraries, schools and local initiatives offered possible routes to access, although their effectiveness depended on resources and local circumstances. Technological diffusion did not erase inequalities inherited from differences in income, age or educational opportunity. Differences in access therefore need to be read together with educational and labour-market data rather than inferred from network statistics alone. The new digital environment therefore enlarged social possibilities while requiring educational and public-policy responses to the forms of exclusion it could produce.

Universities and research institutes experienced an especially substantial change in the technical possibilities offered by high-capacity academic networks. The CESNET association developed a national research infrastructure designed for requirements different from ordinary residential internet access. Researchers needed predictable connectivity for shared datasets, specialised instruments, collaborative computation and communication with partners abroad. In 2004, CESNET introduced dense wavelength-division multiplexing technology, which enabled more effective use of optical fibre through multiple transmission channels. The following year, the core of the CESNET2 network was upgraded to a transmission rate of ten gigabits per second according to the association's historical account. These developments did not make every university connection equally fast, because end-to-end performance also depended on campus networks and connected systems. They nevertheless enlarged the capacity of the backbone through which demanding research and educational services could be provided. The infrastructure also supported activities such as videoconferencing and remote access to resources that would have been difficult to sustain through slower networks. Technological progress in this setting was inseparable from the expertise needed to operate, monitor and continuously improve the network. Academic connectivity thus became a field of engineering development as well as a service supporting scientific work in other disciplines.

Cross-border networking was central to the modernisation of Czech academic information technology during the years following accession. CESNET participated in the European GÉANT

research and education networking environment, continuing connections that had developed before the Czech Republic joined the Union. The GN2 (second-generation GÉANT networking) project beginning in 2005 sought to expand the network towards a hybrid architecture combining routed internet traffic with more specialised optical connections. This approach reflected the changing character of European science, in which researchers increasingly needed dependable paths for large data transfers and time-sensitive applications. In 2006, CESNET interconnected its network with academic networks in Austria and Slovakia, strengthening regional cooperation through technical links rather than political symbolism alone. The network also enabled a high-definition public videoconference in 2006 and international ultra-high-definition video transmissions in 2007. Such demonstrations revealed engineering competence in handling bandwidth-intensive applications, but their wider value depended on the translation of experimental performance into useful research services. A high-speed link could facilitate distributed scientific projects only when participating institutions also maintained adequate equipment and technical personnel. Czech involvement in European networking therefore represented a reciprocal relationship between national capability and continental infrastructure. The country benefited from cross-border connectivity while contributing specialised operational experience to a shared technological system. The result was a more international research environment whose functionality rested on continuing institutional cooperation.

The development of the MetaCentrum computing environment provides a second perspective on Czech research infrastructure during this period. MetaCentrum had originated in the 1990s and later operated within the CESNET association as a platform for computationally demanding scientific tasks. Its significance lay in coordinating computing capacity across participating institutions instead of requiring every project to maintain its own large dedicated installation. Grid computing depended upon mechanisms for allocating jobs, transferring data, managing identities and handling workloads across multiple machines. Researchers could thereby pursue calculations whose resource requirements exceeded those available on an individual workstation or departmental server. The scientific applications were varied, including numerical modelling, physical simulations and analyses of complex research datasets. Such arrangements also introduced organisational questions about access policies, fair allocation and the reliability of services shared by different scientific communities. In 2009, CESNET's historical record identified MetaCentrum as a national grid infrastructure, marking an important moment in its formal recognition. The designation should not be confused with the later establishment of national supercomputer facilities whose construction and operation occurred after the period examined here. By 2010, grid-based resource sharing had nevertheless become a distinctive element of the Czech computational research environment.

European grid and e-science initiatives reinforced the movement towards collaboration through shared computing and networking resources. CESNET participated in the Enabling Grids for E-sciencE (EGEE) initiative, a European project environment that expanded access to distributed computation for researchers. This cooperation connected technical tasks such as middleware development and authentication with the practical requirements of scientific users. Distributed resources were useful only when researchers could submit jobs, obtain results and preserve data without needing to administer every participating computer independently. The challenges

involved software interoperability, operational monitoring, reliable networking and agreements among organisations with different institutional priorities. Czech participation offered opportunities for engineers and scientists to contribute expertise rather than merely consume services designed elsewhere. It also encouraged university research groups to consider whether their computational methods could operate efficiently beyond local hardware configurations. International scientific infrastructure thus became a source of research questions about distributed systems and a means of investigating problems in other disciplines. However, the benefits were conditioned by the quality of user support and by stable national institutional commitments. Because resources were distributed, clear technical documentation and common operating procedures became indispensable to their successful use. The experience illustrates why European research integration should be assessed through sustained technical capability, not through nominal project membership alone.

The modernisation of university computing during these years was not confined to large research networks or shared computational resources. Faculties in Prague, Brno, Ostrava, Plzeň and other university centres faced growing demand for graduates capable of developing and managing complex information systems. Research and teaching programmes increasingly engaged with databases, software engineering, computer security, theoretical informatics and the architecture of distributed applications. International scholarly exchange affected doctoral training by exposing students to collaborative projects and to publication standards extending beyond national academic communities. University departments also had to update laboratories, teaching software and network services while balancing these investments against other educational responsibilities. Participation in European research projects could improve access to partners and specialised methods, but it did not remove competition for experienced academic staff. The growth of commercial information technology created alternative employment opportunities that sometimes made university recruitment and retention more difficult. At the same time, cooperation with businesses enabled applied projects, student placements and the transfer of technical problems into academic inquiry. The resulting relationship between teaching and industry was productive only when universities retained the capacity for independent scientific judgement. By 2010, the preparation of informatics specialists had become increasingly important to both the research system and the expanding market for digital services.

Structural funding and national development programmes changed the institutional conditions under which research capacity could be planned. The European Union's 2007–2013 programming period created opportunities for major research and innovation investment, although approval, contracting and construction followed separate timetables. The Operational Programme Research and Development for Innovation was particularly relevant to the longer-term expansion of Czech scientific infrastructure outside Prague. Its significance for the years before 2011 lies chiefly in project preparation, institutional coordination and decisions about future facilities. Large investments require feasibility studies, professional teams, procurement arrangements and agreements on how equipment will be supported after construction. Consequently, the initial policy and planning stages may be historically important even before a new research centre begins providing services. This distinction is essential in the case of the IT4Innovations National

Supercomputing Center, whose formal establishment and first major systems belonged to the following decade. It would be chronologically inaccurate to describe the fully operating Ostrava supercomputer centre as an achievement completed between 2004 and 2010. The period did, however, prepare conditions for more ambitious national investments by strengthening European funding mechanisms and institutional partnerships. The size of a proposed facility and its eventual scientific importance cannot be inferred from an early funding application alone. Research infrastructure policy therefore connected the consolidation of the 2000s with transformations that would become much more visible in the 2010s.

European financial support was also intended to influence the technological capabilities of enterprises rather than academic institutions alone. The Operational Programme Enterprise and Innovation for 2007–2013 established a policy framework that explicitly addressed innovation, competitiveness and the use of information and communication technologies. Its instruments included support related to information technologies in businesses, strategic services, research facilities and cooperation between companies and research organisations. Such programmes reflected the recognition that equipment purchases alone could not create a durable knowledge-based economy. A firm adopting enterprise software might need changes in accounting practices, inventory management, staff responsibilities and the handling of customer information. Public support could reduce some financial constraints, but it could not substitute for realistic business planning or the technical competence required to complete a project. Regional development objectives also made the geographical distribution of investment an important consideration in evaluating the programmes. The existence of a funding mechanism should not be interpreted as evidence that every supported enterprise achieved lasting productivity gains. Assessment must distinguish the design of an intervention, the projects actually implemented and the measurable outcomes that subsequently followed. Nevertheless, the programmes helped make enterprise digitalisation part of a more explicit national development agenda.

The connection between technological investment and workforce capabilities became more visible as information systems grew more complex. Businesses increasingly required systems administrators, network engineers, database specialists, software developers and personnel able to support users with different levels of technical expertise. An effective digital service also depended on managers capable of specifying requirements and coordinating technical work with ordinary business processes. European integration widened the possibilities for professional mobility while exposing employers to international competition for qualified personnel. Czech graduates could pursue work in foreign companies without necessarily leaving the country, because multinational employers developed engineering and service activities within Czech cities. Conversely, domestic companies could reach clients elsewhere in Europe by demonstrating technical quality and communicating effectively across languages and commercial cultures. The resulting labour market rewarded specialist expertise, but it also increased pressure for continuing education as software platforms and security requirements changed. Universities and professional training providers consequently faced expectations to develop practical skills without reducing informatics education to the operation of contemporary commercial products. The most durable capacity was the ability to understand systems, learn

new technologies and assess their limitations independently. Continuing education thereby became part of technological competitiveness rather than merely a response to shortages in particular technical occupations. Human expertise therefore remained a decisive component of digital development even as network speeds and software capabilities improved.

International technology firms influenced the Czech information technology industry through investment, employment and organisational knowledge. Their activities ranged from software development and business services to technical support, systems integration and the management of international customer relationships. Czech locations offered combinations of engineering education, established industrial capabilities and access to European markets that were attractive for certain specialised operations. The growth of multinational centres exposed employees to cross-border project management, quality assurance and operating standards used by large organisations. Such exposure could strengthen professional capabilities and create opportunities for employees who later moved to smaller firms or established enterprises of their own. Nevertheless, the presence of a foreign-owned development facility does not make every product produced there an independently originated Czech innovation. Equally, judging a national industry only by locally headquartered firms would overlook substantial work performed by engineers employed within international companies. A meaningful account must distinguish ownership, location of research activity, origin of intellectual contributions and destinations of commercial revenue. The period also demonstrated that foreign investment and domestic entrepreneurship were not mutually exclusive routes towards technological upgrading. Their relative value depended on the kinds of competencies, research activity and decision-making authority developed within the country.

The Czech software market became increasingly diverse as commercial clients moved beyond the basic installation of personal computers and office applications. Businesses purchased specialised systems for accounting, document management, customer relationships, manufacturing and the coordination of geographically distributed operations. The growing importance of software integration reflected a practical problem: new applications had to communicate with databases, procedures and equipment already in use. For developers, technical reliability depended on requirements analysis, testing, maintenance and the management of successive versions rather than on writing source code alone. Support contracts and long-term relationships with customers became important because information systems often required adaptation after their initial introduction. Some Czech suppliers developed specialised products, while others earned revenue through implementation, consultancy and outsourced development for international organisations. These business models created different kinds of employment and opportunities for intellectual-property development. The adoption of commercial software did not automatically indicate that its principal algorithms or underlying platforms had been invented in the Czech Republic. Nevertheless, the capability to customise, integrate and sustain complex systems represented a meaningful form of engineering expertise. The capacity to sustain a product after delivery became particularly important as customers increasingly depended upon continuous access to digital records. By the end of the decade, the software sector had become more differentiated in both its products and its relationship with customers.

The evolution of Seznam.cz illustrates how domestic internet enterprises could combine Czech-language knowledge with increasingly sophisticated technical services. The company had emerged in the previous decade, but its development after 2004 reflected an expanding market for search, electronic mail, advertising and digital information. According to its corporate history, Seznam integrated Email.cz into its own mail service in 2004 and launched a proprietary search engine in March 2005. The initial Czech web index contained approximately thirty million documents, providing a concrete indication of the system's technical ambition at that stage. In 2006, the company introduced Sklik, its own pay-per-click advertising system, and expanded interactive mapping services. These developments mattered because a local internet portal was becoming a more complex technological platform rather than a directory of external links. Search required crawling, indexing and relevance assessment, while advertising services depended on data processing and functioning commercial relationships. The evolution of Mapy.cz combined geographical information, interface design and increasingly substantial demands on storage and server capacity. The company's position also reflected the value of language and local market familiarity in competition with much larger international enterprises. Its achievements are best assessed through identifiable products and engineering developments rather than through assertions of national technological superiority.

The wider market for portals, online media and digital content expanded with the growth of broadband and more frequent household internet use. Czech-language news services, electronic mail, discussion platforms and entertainment websites attracted audiences whose daily routines were increasingly mediated by online information. For publishers, digital distribution created possibilities for more frequent updates and new methods of understanding audience behaviour. For advertisers, search-related and display advertising introduced alternative ways of reaching customers compared with print, television or outdoor promotion. The technical foundations of these services included content-management systems, server infrastructure, web analytics and increasingly interactive user interfaces. Domestic providers competed not only with each other but also with foreign companies whose services could operate across national borders. The continued strength of some Czech-language platforms showed that linguistic adaptation and local editorial knowledge could remain commercially significant. However, audience size alone cannot demonstrate software originality, and the growth of media consumption should not be confused with a fundamental advance in computer science. This distinction is necessary when interpreting the industry as part of a book concerned with both research innovation and technological entrepreneurship. The rapid growth of online communication also made accessibility and the quality of Czech-language information increasingly significant public concerns. The market nevertheless broadened the range of practical activities through which Czech businesses acquired experience in large-scale digital services.

Electronic commerce became a more visible component of the digital economy as connections improved and confidence in online transactions developed. The Czech Statistical Office's 2005 survey recorded that only a small proportion of the population had purchased goods or services online during the preceding year. By 2010, its later historical account described internet purchasing as an activity undertaken by approximately one quarter of individuals. This change reflected more than the growth of websites, because commercial transactions required payment

arrangements, order processing, customer support and dependable distribution. Retailers needed product databases and mechanisms for keeping prices and stock information sufficiently accurate to support purchasing decisions. Comparison services reduced some information costs for consumers but also intensified competition among businesses offering similar goods. Delivery networks and the availability of payment on receipt remained important in an environment where not all customers were equally willing to make electronic payments. The emergence of specialised online marketplaces and established retailers' web shops therefore relied on coordination between digital systems and physical commercial operations. Greater purchasing convenience could coexist with concerns about fraud, privacy and the reliability of unfamiliar sellers. The growth of electronic commerce was consequently an organisational transformation of retail as well as an increase in consumer internet activity.

Digital financial services developed alongside commerce but introduced distinct requirements for security and customer trust. Online banking allowed users to inspect accounts and perform certain transactions without visiting a branch, changing the relationship between financial institutions and their clients. The diffusion of such services depended on authentication methods, protected connections, clear user interfaces and procedures for responding to errors or suspected misuse. Banks had incentives to improve electronic channels because they could lower the cost of routine transactions while offering greater customer convenience. At the same time, electronic delivery transferred some responsibility for recognising suspicious messages and protecting credentials to ordinary users. Financial organisations therefore had to combine software development with security monitoring, customer education and compliance with the applicable regulatory framework. The growth of internet banking was not identical to the adoption of online shopping, because financial services involve different kinds of personal data and risk. Nevertheless, familiarity with one kind of secure online interaction could contribute to willingness to use other digital services. Czech statistical surveys recorded expanding interest in internet banking during the second half of the decade, although participation remained unequal among social groups. These requirements created opportunities for specialised software suppliers as well as additional operational responsibilities for financial institutions. The financial sector thus offers a useful example of technological consolidation driven by service redesign and the institutional management of trust.

Enterprise statistics reveal that businesses followed a somewhat different trajectory from households because many had already acquired internet access before mass residential broadband became common. A Czech Statistical Office series for enterprises with at least ten employees reported internet access in approximately ninety-five per cent of such firms in the middle of the decade. Broadband connectivity among the surveyed enterprises was also widespread, although the corresponding measures require attention to the survey's coverage and reference dates. These figures should not be transferred to microenterprises, which often had different budgets, staffing arrangements and technical needs. Moreover, access to the internet does not establish that an organisation has integrated digital tools effectively into production, management or customer relations. Some firms used networking primarily for correspondence and information retrieval, while others developed sophisticated systems for procurement and supply-chain coordination. The introduction of enterprise resource planning or electronic sales

systems required organisational changes that could involve several departments. A company might possess advanced equipment and still struggle to maintain consistent data or implement appropriate information-security procedures. The distinction between availability and effective use is therefore central to evaluating the digital modernisation of Czech enterprises. Statistical connectivity measures describe important enabling conditions, but they do not provide a complete measure of productivity or innovation.

Information security became increasingly important as the number of connected households, enterprises and institutions expanded. Czech developers had already established a substantial position in antivirus software through companies whose roots predated European Union accession. During the following years, the security-software market became more international and diversified beyond the detection of traditional computer viruses. The Brno-based company Grisoft, associated with the Anti-Virus Guard (AVG) product family, received significant investment in 2005 from a group including Enterprise Investors and Intel Capital. Its 2006 acquisition of the German company ewido networks broadened the range of malware-protection technologies offered to customers. These developments demonstrate how Czech-origin software businesses could acquire capital, technologies and customers through international commercial relationships. The evolution of Alwil, associated with Avast, likewise reflected the opportunities created by online distribution and the expanding global demand for endpoint protection. A company maintaining antivirus protection needed continuing research into malicious code, frequent updates and systems capable of supporting users in multiple countries. The achievement was therefore not merely the sale of a software package but the development of organisational and engineering capabilities that could be sustained over time. Investment and acquisition histories also reveal the increasing internationalisation of decision-making within successful Czech-origin technology companies. Corporate growth should nevertheless be distinguished from the separate scientific question of whether a particular detection method was original or technically influential.

The increasing complexity of security problems also changed the responsibilities of national research and communications infrastructure providers. As networks became essential to academic work, their operators needed procedures for detecting incidents, coordinating responses and sharing information about vulnerabilities. CESNET established its CSIRT.CZ (Computer Security Incident Response Team for the Czech Republic) incident-response activity in 2008, providing an institutional example of security capacity developing within the research-network environment. In 2010, this team obtained formal recognition as a national computer security incident response team according to the association's historical account. Incident response differs from commercial antivirus development because it concerns coordination among organisations and the handling of events affecting network operations. Both activities nevertheless depend on technical expertise, rapid exchange of information and the ability to distinguish credible threats from ordinary system behaviour. Research institutions also faced growing requirements for authentication and secure access when computational resources were shared across administrative boundaries. The historical record illustrates that cybersecurity was becoming an institutional function rather than simply a feature purchased with individual software products. Later national cybersecurity legislation and authorities should not be

projected backwards as if their mature organisational forms had already existed by 2010. The decade instead laid foundations through specialist teams, practical coordination and a clearer understanding of network-level risks.

Electronic government developed in parallel with commercial online services, but the redesign of public administration involved different legal and organisational constraints. State authorities needed to preserve authoritative records, protect personal information and demonstrate the procedural validity of electronic communication. A public-facing website could improve access to information without changing the underlying process by which an official decision was prepared or delivered. Consequently, the shift towards electronic administration required attention to document standards, identity verification and the responsibilities of separate agencies. The government's Smart Administration Strategy, approved in July 2007, placed the improvement of public services within a broader programme of administrative modernisation. Its objectives went beyond introducing computers and addressed the effectiveness, accessibility and coordination of public institutions. European funding programmes could support technical components, but implementation still depended on organisational cooperation and legislative consistency. The challenges were particularly demanding in a system composed of central authorities, municipalities and specialised administrative bodies. Changes that simplified one transaction could expose unresolved difficulties in information exchange between institutional databases. Effective coordination between agencies required a degree of shared procedural understanding that could not be purchased as a technical product. Digital government thus became a test of the capacity to reform procedures through technology rather than to automate inherited bureaucracy unchanged.

The Czech POINT (Český Podací Ověřovací Informační Národní Terminál) system provides a concrete example of how authorities attempted to make administrative information more accessible during the period. The contact-point network began operating in 2007 and offered residents a means of obtaining selected official extracts through designated public-service locations. The model was significant because it connected electronic information systems with physical offices that many citizens already used and trusted. It did not presume that every person possessed a computer, sufficient technical knowledge or a secure internet connection at home. Instead, a trained public employee could mediate access to digital records while preserving an officially recognised form of documentation. Czech POINT thus demonstrates that public-sector digital innovation may take a hybrid form combining electronic processing with personal assistance. The service also depended on the availability and reliability of the registries from which information was retrieved. Official accounts of its first year recorded substantial demand, indicating that the system addressed practical administrative needs rather than only symbolic technological objectives. Nevertheless, the ability to issue extracts should not be mistaken for full integration of all governmental databases or the complete elimination of paper procedures. Its historical importance was to make selected electronic public services operational and socially accessible within the constraints of the late 2000s.

The introduction of data boxes represented a further step towards legally recognised electronic communication with public authorities. Act No. 300/2008 of the Czech Collection of Laws established the legal basis for electronic acts and authorised document conversion, with central

provisions taking effect on 1 July 2009. The resulting system of datové schránky, or data boxes, provided an official electronic channel through which eligible institutions and users could exchange documents. Its function differed from ordinary electronic mail because legal delivery, identification and procedural responsibilities were defined within a dedicated institutional framework. For public bodies, electronic delivery offered a way to standardise certain communications and reduce dependence on traditional postal processes. For users, however, the new system also required understanding the legal significance of messages and the obligations associated with receiving them. The reform therefore involved information technology, legislation and administrative behaviour at the same time. It should be evaluated through actual use and procedural consequences rather than by describing the creation of an electronic mailbox as a complete transformation of government. Plans for the integration of basic public registers were also developed around this period, although their full operational launch occurred later, in 2012. Authorised electronic conversion offered a bridge between documents created on paper and records intended for legally valid electronic processing. The years to 2010 consequently marked a substantial institutional beginning rather than the completion of comprehensive digital public administration.

Education and social participation reveal the broader consequences of a period often described mainly through companies, networks and administrative reforms. By 2010, schools had more computers available to pupils than in the middle of the decade, and connections of higher capacity had become increasingly common in educational institutions. The Czech Statistical Office reported approximately thirteen and a half computers per hundred pupils and students in basic and secondary schools in 2010, compared with nearly nine in 2005. These improvements created opportunities for teaching digital literacy, researching information and communicating through educational platforms. Yet the pedagogical value of technology still depended on teachers' preparation, appropriate materials and the ability to integrate computers into meaningful learning activities. The expansion of internet services also influenced how adults searched for employment, accessed professional information and maintained social relationships. Digital inclusion remained incomplete because older users, individuals with limited resources and people outside major urban centres did not benefit equally. National policy therefore faced a continuing challenge of connecting technical infrastructure with the development of accessible services and human capabilities. A digitally connected school or office could contribute to modernisation only when the technology supported rather than displaced its educational or institutional purposes. The wider social history of the decade illustrates the interaction between connectivity, opportunity and persistent inequalities.

By the end of 2010, Czech information technology had acquired an institutional and commercial depth substantially different from its position at European Union accession. Broadband had expanded into a major household service, while academic networks operated sophisticated optical technologies and supported distributed research computation. Czech software enterprises were increasingly integrated into international markets, and multinational employers contributed to a more diverse technological labour market. Electronic commerce, online banking and digital media had begun to alter familiar patterns of consumption and communication. Public administration had introduced important systems such as Czech POINT and data boxes, even

though the transformation of its underlying procedures remained incomplete. European research cooperation and development funding enlarged the range of projects that institutions could plan and undertake. Nevertheless, persistent disparities in access, professional skills and organisational capacity limited the benefits obtainable from new infrastructure. Several highly visible achievements of the following decade, especially new large supercomputing facilities and more mature integrated digital government, were still in preparation rather than in operation. The period from 2004 to 2010 should therefore be characterised as one of consolidation, selective modernisation and deeper European integration rather than the final achievement of digital maturity. These foundations made subsequent digital expansion possible without predetermining the pace or success of every later initiative. Its most important legacy was the creation of networks, institutions and professional relationships capable of supporting a more ambitious technological transformation after 2010.

2011–2020: High-Performance Computing, Cybersecurity, Digital Entrepreneurship and the Rise of Advanced Information Technologies

The period from 2011 to 2020 constituted a decisive stage in the maturation of computer science and information technology (IT) in the Czech Republic, although its significance cannot be reduced to the acquisition of faster computers or the commercial success of individual firms. During these years, computing became more firmly embedded in national research infrastructure, public security policy, industrial innovation and the ordinary activities of households and enterprises. The country entered the decade with established universities, an increasingly sophisticated academic network, capable software businesses and a growing population of digitally connected users. It nevertheless faced an important question about whether these inherited resources could support original research and high-value technological activity rather than primarily the consumption or local adaptation of international products. Investment in supercomputing, cloud infrastructure and specialised laboratories broadened the range of scientific problems that domestic institutions could investigate. At the same time, machine learning, data-intensive analysis and network security acquired greater prominence within universities, corporate research groups and government organisations. Entrepreneurial development also changed as Czech-founded companies sought external investment, international customers and access to the organisational capacities necessary for expansion. These developments interacted, but scientific infrastructure, commercial scale and administrative digitalisation followed different institutional logics and should be examined separately. A large computing installation was not automatically evidence of a nationally originated algorithm, just as the foreign acquisition of a Czech firm did not erase its earlier technological contribution. The defining characteristic of the decade was therefore the formation of a more interconnected digital ecosystem in which research capability, public responsibilities and entrepreneurial opportunities increasingly influenced one another.

At the beginning of the 2010s, Czech digital development remained marked by differences between metropolitan research centres, industrial regions and smaller municipalities. Prague concentrated major university departments, government institutions and corporate offices, whereas Brno combined an important informatics tradition with industrial engineering and a growing technology labour market. Ostrava possessed expertise in technical computing and applied mathematics that could be developed into a more ambitious national research infrastructure. Regional specialisation provided opportunities for complementary scientific roles, although it also meant that equipment, investment and specialised careers were not distributed evenly across the country. The legacy of the previous decade was particularly visible in established programmes of computing education, network engineering, information security and enterprise software. These capacities made new projects plausible because complex infrastructures require trained administrators, researchers and programmers in addition to financial resources. Yet rising expectations also exposed shortages of highly specialised personnel and the difficulty of competing internationally for experienced engineers and doctoral graduates. Some commercially attractive activities, including software services and corporate development, offered career prospects that university departments struggled to match. The resulting relationship between academic research and private employment was productive in many cases but could also place pressure on the continuity of scientific groups. Consequently, the decade should be interpreted as a period of selective capability building rather than an even or automatic transition to technological leadership. The national challenge was to transform accumulated competence into research environments and firms capable of sustaining development over time.

Public and European investment frameworks strongly influenced the pace and geographical direction of this transformation. Projects supported through the operational programmes of the European Union (EU) helped universities create facilities whose initial capital costs would otherwise have been difficult to finance from ordinary departmental budgets. The investment cycle associated with the years 2007–2013 continued to affect research capacity well into the following decade, because buildings, equipment and institutional arrangements could take several years to complete. The subsequent 2014–2020 programming period created further possibilities for developing research infrastructure, professional training and cooperation between universities and external partners. However, European co-financing did not relieve national institutions of the responsibility to provide qualified staff, maintenance and sustainable operational funding. A sophisticated laboratory could quickly lose scientific value if support for software, energy, upgrades or technical expertise failed to continue after construction. The principal historical issue was therefore not simply the total amount invested but the extent to which new resources were integrated into continuing research programmes. Open access to computing time and collaboration with external users helped connect infrastructure expenditure to scientific questions across several disciplines. Project-based investment also encouraged researchers to work across institutional boundaries and to develop forms of administration suited to international consortia. Nevertheless, dependence upon competitive project cycles could complicate the maintenance of long-term expertise in fields that required continuous development. The evaluation of these programmes must consequently include institutional continuity and research use rather than construction schedules alone. The combination of large

capital projects and smaller investigator-led programmes became an important structural feature of Czech computer science during the decade.

The emergence of IT4Innovations at VSB–Technical University of Ostrava was among the clearest institutional expressions of the new ambition in scientific computing. The Centre of Excellence project formally began in 2011, with the intention of creating a national facility supporting high-performance computation and associated research. Its first major system, Anselm, became available to users in 2013 and had a theoretical peak performance of approximately 94 teraflops. The supercomputer offered a level of computational capacity that was difficult for ordinary research departments to reproduce using separate local servers. The opening of the dedicated IT4Innovations building in 2014 established a more permanent physical and organisational setting for the project. These developments required systems administration, interconnection technology, storage provision, job scheduling and procedures for allocating resources among different research teams. The centre's significance accordingly extended beyond the purchase of processors, since users needed expert assistance to adapt demanding calculations to parallel architectures. Czech and international researchers could submit projects requiring specialised resources, thereby linking infrastructure operation to scientific peer assessment and collaboration. Anselm supported work in areas including materials research, chemistry, environmental modelling and engineering, where computational methods supplement experimental or theoretical investigations. Its arrival changed the practical opportunities for researchers while leaving the originality of individual scientific results to be evaluated through publications, methods and reproducibility.

A further expansion occurred when the Salomon supercomputer entered service in 2015 with a theoretical peak performance of approximately two petaflops. The system ranked fortieth in the TOP500 list at its introduction, drawing international attention to the scale of computing resources then available in the Czech Republic. Such a ranking was an indicator of benchmarked computational capability rather than a direct measure of the quality of scientific ideas produced with the equipment. Researchers nevertheless gained access to a platform suitable for simulations involving large datasets, complex physical models and demanding numerical procedures. The scientific potential of a petascale system depended on parallel algorithms, efficient communication among computing nodes and careful management of memory and storage. Workloads that were inefficiently designed could consume extensive machine time without producing results proportionate to their cost. This created opportunities for computer scientists concerned with numerical performance, optimisation, code portability and resource allocation. The relationship between specialist computing research and external scientific users became particularly important because improvements in computational methods could benefit many disciplines simultaneously. Salomon also strengthened the position of Ostrava within European conversations about national supercomputing services and shared research infrastructure. Its historical importance lies in a combination of increased technical capacity, specialised expertise and the institutionalisation of access to complex computing facilities. It would be misleading, however, to treat every simulation undertaken on the machine as an innovation that originated exclusively within Czech computer science.

During the final years of the decade, the infrastructure in Ostrava expanded towards workloads associated with data analytics and artificial intelligence. The Barbora supercomputer entered service in 2019 with a theoretical peak performance of approximately 849 teraflops, complementing the existing computational environment. In the same year, a specialised NVIDIA DGX-2 system increased the capacity available for calculations using graphics accelerators and machine-learning methods. Conventional scientific simulations and the training of neural networks place partly different demands on processor architecture, memory organisation and data movement. Their coexistence therefore encouraged infrastructure managers to think beyond a single model of high-performance computing. The Czech Republic also joined the European High Performance Computing Joint Undertaking (EuroHPC JU) in 2018, reflecting the increasingly multinational organisation of advanced computing resources. In 2019, IT4Innovations participated in a consortium selected to host one of the major European supercomputing systems, although the subsequent installation belonged to a later historical stage. Plans for future equipment should not be confused with completed installations when describing national capabilities in 2020. More fundamentally, European partnerships allowed Czech computing specialists to contribute to a shared technological landscape that no medium-sized research system could reproduce in its entirety. By the end of the decade, Ostrava had become a strategically important location for both computational service provision and research into methods that improve the utilisation of such facilities.

Supercomputing did not develop in isolation from the distributed resources already available through the Czech academic computing environment. MetaCentrum, organised within the CESNET (Czech Education and Scientific Network) research and education network, provided users with access to computing resources distributed across institutional sites. This approach differed from the architecture of a single large supercomputer because workloads were scheduled across clusters that could vary in configuration and availability. For many research tasks, distributed computing offered an appropriate balance of flexibility, accessibility and computational performance. The environment also required expertise in authentication, resource management, software dependencies and the reliable transfer of information between sites. Researchers became increasingly accustomed to treating computing as a managed scientific service rather than as equipment owned exclusively by their department. A shared allocation model could reduce unnecessary duplication while broadening access for smaller research groups without substantial local infrastructure. Nevertheless, computational services still needed effective user support, clear operational policies and technical documentation if their theoretical capacity was to be used efficiently. The development of national computing services therefore involved organisational and educational innovation as well as changes in hardware. It also provided an important foundation for later efforts to offer more coherent access across networking, cloud, storage and supercomputing services. The long-term achievement was the gradual emergence of an institutional culture in which access to advanced digital resources could be treated as part of ordinary research practice.

Brno developed a complementary approach to scientific computing through the CERIT Scientific Cloud (CERIT-SC) centre at Masaryk University. The underlying infrastructure project ran from 2011 to 2014 and built on earlier computing expertise within the university. CERIT-SC aimed to

provide flexible computational and storage resources while maintaining closer cooperation with users whose research requirements could change rapidly. Cloud-oriented services were attractive because researchers increasingly needed environments that could be provisioned, modified and combined without purchasing dedicated equipment for every project. The scientific challenge extended beyond virtualisation, since useful infrastructure required scheduling, security, data management and applications adapted to disciplinary problems. The centre worked with research communities for whom computation was essential but not necessarily their principal field of expertise. Its model therefore emphasised partnership with users rather than only the delivery of standardised technical capacity. Subsequent research infrastructure support between 2016 and 2019 helped preserve and extend this role. Developments in Brno showed that the national computing ecosystem benefited from more than one architectural solution, with cloud systems complementing large supercomputers and distributed grids. The centre also contributed to a regional environment in which informatics research, applied scientific work and infrastructure operation could reinforce one another.

The national research and education network CESNET underwent major changes as the volume and complexity of scientific communication increased. In 2012, important backbone routes were upgraded to capacities of 100 gigabits per second, expanding the possibilities for transferring research data between connected institutions. Additional data repositories and authentication-related services helped researchers manage the practical requirements of distributed projects. Experimental transmission at 400 gigabits per second was demonstrated in 2015, while the connection to the pan-European GÉANT network was strengthened to 100 gigabits per second in 2016. These milestones represented different types of achievement, since a laboratory transmission demonstration was not equivalent to a nationwide production service of the same capacity. Greater bandwidth was valuable for scientific fields generating large datasets, including particle physics, imaging, bioinformatics and high-resolution visualisation. The usefulness of such connections nevertheless depended upon end-to-end reliability, security controls and adequate capacity at participating laboratories. Network engineering itself became an active area of expertise involving optical transmission, monitoring, routing and the optimisation of services. CESNET also participated in international exchanges that helped Czech institutions operate within common research-network standards. By the end of the decade, the network was no longer merely an instrument for accessing information but part of the technical fabric through which scientific experiments and collaboration were organised. This changing role provides an essential context for understanding the growth of data-intensive research in Czechia.

As academic networks grew more sophisticated, their operators increasingly integrated security analysis, identity management and collaborative services into everyday infrastructure provision. The forensic laboratory opened by CESNET in 2013 represented a specific investment in investigating digital incidents and understanding the technical behaviour of compromised systems. Other projects developed monitoring and incident-information systems, including approaches associated with the Warden and Mentat platforms. These systems were designed to help transform large volumes of network observations into information suitable for operational response and collaborative analysis. Their development illustrates the distinction between routine network administration and research-informed engineering, where new tools emerge

from particular technical challenges. Data exchange across administrative domains could improve the detection of suspicious activity while also raising questions about confidentiality and lawful information handling. Institutions had to accommodate rapidly evolving attack methods without obstructing legitimate scholarly communication or imposing unnecessary restrictions on users. Training and the cultivation of specialist security teams therefore became as important as the deployment of individual monitoring devices. The experience accumulated in academic networks was relevant to the wider national discussion about cyber resilience, even though university systems and state security institutions served different constituencies. Network security increasingly became a collaborative discipline joining technical analysis, incident response, software development and institutional governance.

The separate research infrastructures increasingly recognised the advantages of closer coordination across high-speed networking, cloud resources and major supercomputing systems. In 2019, CESNET, Masaryk University and VSB–Technical University of Ostrava prepared a joint initiative intended to integrate their services within the national e-INFRA CZ framework. The arrangement brought together CESNET, CERIT Scientific Cloud and IT4Innovations as complementary components rather than seeking to replace their institutional identities. Its launch in 2020 gave the country a more coherent organisational structure for transferring, storing and processing research data. Such integration mattered because scientific teams often require several services at once and can be hindered by incompatible administrative procedures or fragmented technical support. Researchers may need to transfer observations securely, store them for later reuse, perform large calculations and share results with collaborators in different institutions. An integrated infrastructure can simplify these activities, but meaningful interoperability remains a continuing technical and organisational task. The initiative also strengthened the visibility of Czech research computing within European conversations about scientific data and access to shared resources. When the coronavirus pandemic disrupted academic work in 2020, the participating infrastructures assisted institutions facing sharply increased demand for remote collaboration and computational services. The new structure thus emerged at the point when a public-health emergency made the social value of dependable digital research infrastructure especially apparent. Its formation marked an organisational achievement of the decade rather than the completion of every integration task it had set for itself.

The establishment of the Czech Institute of Informatics, Robotics and Cybernetics (CIIRC) at the Czech Technical University in Prague represented a particularly visible institutional response to these changing research priorities. The institute was founded in July 2013 to strengthen the integration of research and education across computing, automation and related disciplines. Its objectives combined fundamental investigation with the development of results potentially relevant to industry and public services. The move to a dedicated building in Prague's Dejvice district in April 2017 gave the institute a stronger basis for laboratories, interdisciplinary projects and international recruitment. CIIRC brought together interests including machine perception, robotics, learning algorithms, optimisation and the design of intelligent systems. These directions shared mathematical and computational foundations but addressed different research questions and application environments. The institute also sought to connect university research with programmes in industrial automation and the practical demands of firms. Such an

arrangement could facilitate knowledge exchange, although cooperation with companies did not by itself guarantee scientific originality or economically successful products. Training postgraduate researchers within active interdisciplinary teams was an important element of the longer-term institutional ambition. CIIRC consequently exemplified the movement towards research organisations designed around interconnected technological problems rather than narrowly separated academic departments.

Machine learning and data science became more visible during the second half of the decade as access to computational resources and electronic data expanded. Researchers developed and adapted methods for recognising patterns in images, speech, written language and complex records. The international progress of deep neural networks encouraged Czech research groups to investigate architectures whose performance depended upon extensive training data and substantial computational power. Such work required careful choices about datasets, evaluation procedures and the difference between performance in laboratory conditions and reliability in practical use. Language technologies were particularly relevant in a country with strong traditions of corpus linguistics and computational treatment of the Czech language. Research on morphological analysis, speech recognition and machine translation connected specialist linguistic knowledge with statistical methods and learning systems. Meanwhile, computer vision investigations supported applications in robotics, industrial inspection and the interpretation of scientific imagery. These areas differed in their scientific objectives, and the adoption of an existing international model should not be mistaken for a new theoretical contribution. Originality could arise instead through new methods, improved resources for a particular language or demonstrably better performance under clearly defined conditions. The growing demand for such capabilities encouraged cooperation between academic groups, software firms and computing centres. By 2020, data-driven methods had become a central part of the national research agenda without replacing symbolic, probabilistic or formally grounded approaches.

The interaction between artificial intelligence and industrial research became more structured as Czech institutions sought to address the needs of advanced manufacturing. This orientation was influenced by the wider European discussion of Industry 4.0, a term covering interconnected production systems, industrial data and increasingly autonomous technological processes. In Czechia, it was particularly relevant because manufacturing remained a major component of economic activity and employed many engineers trained in applied computing. Research groups investigated robot coordination, adaptive control, industrial sensing and the exchange of information between physical machinery and digital models. At the same time, industrial firms often faced practical obstacles involving legacy equipment, cybersecurity requirements and uncertainty about the financial return from substantial upgrades. In 2019, a Czech–German partnership launched the Research and Innovation Centre on Advanced Industrial Production (RICAIP) project within European research programmes. Partners included CIIRC in Prague, the Central European Institute of Technology at Brno University of Technology and specialist German research organisations. The initiative aimed to connect experimental production testbeds and investigate solutions suitable for advanced industrial systems. Its establishment was a significant organisational development, but the full realisation of the project's infrastructure and subsequent results extended beyond 2020. The example demonstrates how the decade

increasingly linked academic computing research to collaborative experiments addressing real manufacturing environments.

Robotics and computer vision provided additional examples of the convergence between theoretical computing and technologies deployed beyond university laboratories. Robots operating in uncertain surroundings need methods for perception, localisation, decision-making and the safe control of physical movement. Industrial cameras require robust image-processing procedures able to cope with variations in illumination, movement and the characteristics of manufactured objects. Autonomous behaviour similarly depends on algorithms that must function under explicit restrictions involving computation time, available information and the consequences of error. Researchers at Czech technical universities and associated centres worked within international communities examining such problems from mathematical, software and engineering perspectives. The establishment of interdisciplinary institutions enabled computer scientists to interact more closely with specialists in sensors, electronics and mechanical systems. This cooperation mattered because the performance of an intelligent machine depends on the entire system rather than on its learning algorithm alone. Simulated experiments could accelerate design, but transferring a procedure from a virtual setting to physical equipment introduced additional uncertainties. Successful research therefore required carefully designed tests and attention to failure modes, not simply visually impressive demonstrations. The expansion of these activities made robotics a productive meeting point between Czech computing traditions and industrial technological development. It also showed why advanced information technologies should be analysed through both conceptual innovation and the practical conditions of their application.

Cybersecurity acquired a more clearly defined institutional position as reliance upon digital networks expanded across the economy and public administration. The Czech government decided in October 2011 that the National Security Authority would carry responsibility for cybersecurity and supported the creation of a specialised national centre. This decision reflected an understanding that network incidents could affect critical services as well as the private interests of individual users. The legal process that followed culminated in Act No. 181/2014 Coll. on Cyber Security, which entered into effect on 1 January 2015. The legislation established a framework for obligations and procedures connected with designated information systems and significant cyber incidents. Its importance lay in moving cybersecurity from a set of largely separate technical practices towards a more explicit field of public responsibility. Organisational duties could not eliminate technological vulnerabilities, but they could clarify which institutions had to manage risks and share information. The national framework also needed to account for the practical differences between telecommunications operators, critical infrastructure and ordinary enterprises. Effective implementation depended on specialists capable of understanding systems architecture, incident response and the sometimes competing requirements of security and service continuity. The regulatory transition thus created professional and scientific challenges that extended well beyond the drafting of legislation.

The next institutional milestone occurred on 1 August 2017, when the National Cyber and Information Security Agency (NÚKIB) began operating as a separate central administrative authority. The new organisation assumed responsibilities for national cybersecurity, including

specialised duties concerning secure information and communication systems. Its establishment represented a change in public administration rather than the sudden creation of technical expertise from nothing. Earlier arrangements within the National Security Authority and the National Cyber Security Centre had already developed staff, procedures and professional relationships. A dedicated agency could nevertheless provide a more identifiable institutional centre for coordination, regulation and response. These responsibilities became increasingly relevant as public services, telecommunications and private enterprises relied on tightly interconnected digital environments. The agency's role should be distinguished from commercial cybersecurity firms, which develop products and services within competitive markets rather than exercising statutory authority. Both sectors could benefit from cooperation with universities, but their objectives, obligations and forms of accountability remained different. The international nature of cyber threats also required communication with partners outside the Czech Republic and awareness of developing European security expectations. By the end of the decade, national cybersecurity had become a more established domain of public policy, professional training and technological research. This development contributed to the distinctive position of security within the country's wider digital ecosystem.

Brno emerged as an especially important environment for connecting academic cybersecurity research with practical exercises and professional training. Masaryk University developed the KYPO Cyber Range Platform from 2013 as a virtual environment for reproducing security scenarios in a controlled setting. A cyber range enables learners and researchers to investigate attacks, defence procedures and organisational responses without exposing an ordinary production network to the same risks. Such environments support education because practical incidents involve a sequence of decisions, imperfect information and interactions between several technical systems. They can also help investigators evaluate tools and training methods under conditions that are more systematic than improvised classroom demonstrations. The value of a cyber range does not lie merely in simulating a threatening computer screen, since meaningful exercises require realistic configuration, clear objectives and careful assessment. The Masaryk University initiative connected specialist technical expertise with educational approaches appropriate to university students and professional communities. In 2020, the KYPO Cyber Range Platform was released as open-source software, extending opportunities for external adoption and collaborative development. This milestone represented a different type of innovation from a commercial security product because it emphasised shared tools for research and professional preparation. The combination of academic capability, training infrastructure and practical cybersecurity needs strengthened Brno's importance within the national digital environment.

The commercial cybersecurity industry provided another, more internationally visible, dimension of Czech information technology development. Avast and AVG, both rooted in the earlier history of Czech software entrepreneurship, entered the decade with established security products and substantial markets outside the country. Their business success depended on continuing software development, the maintenance of threat-detection capabilities and the ability to distribute products to large numbers of users. In July 2016, Avast announced an agreement to acquire AVG in a transaction valued at approximately 1.3 billion United States dollars. The

companies began operating together following the completion of the acquisition of a controlling interest later that year. The merger changed the scale and organisational structure of the enterprise, but it should not be interpreted as evidence that the two original research and engineering traditions had become identical. In May 2018, Avast entered the London Stock Exchange, raising international visibility and accessing capital markets on a scale unusual among Czech-founded technology companies. Such developments illustrated the possibilities for commercial growth in cybersecurity, where products could serve international customers without physical distribution networks comparable to those of traditional manufacturing. At the same time, ownership transactions and market valuations measured corporate circumstances rather than the scientific novelty of every security technique deployed by the business. The importance of Avast and AVG to the decade therefore encompasses original entrepreneurial development, international market reach and the consolidation of industrial expertise in information security. Their history also raises questions about how nationally rooted innovation interacts with the global organisation of technology capital.

The wider domestic software and internet economy continued to diversify beyond the internationally prominent security industry. Seznam.cz maintained a distinctive position as a Czech-language digital platform operating in a market strongly influenced by global search and advertising companies. Domestic providers developed online services adapted to local consumers, advertisers and businesses, including specialised information services and electronic commerce. The value of such enterprises often derived from combining software engineering with an understanding of language, user behaviour and the organisation of the Czech market. Competition nevertheless intensified as global platforms expanded mobile applications, online advertising infrastructure and access to international customer data. Local success could not therefore be treated as evidence that Czech firms controlled the underlying global technologies used across all digital services. For firms serving the home market, the principal questions concerned sustainable revenue, product differentiation and the capacity to retain skilled staff. Other companies developed enterprise software and specialist services for international customers, pursuing business models less dependent on a large domestic population. These different strategies reveal why the IT industry cannot be measured solely through the visibility of consumer-facing internet brands. By the late 2010s, Czech software entrepreneurship encompassed local platforms, business-to-business applications and export-oriented specialised products rather than a single unified corporate model.

Kiwi.com provides a revealing example of how a company founded during the decade could use software to reorganise an established service market. The business began as Skypicker in Brno in 2012 and developed technology for combining flights and routes that were not necessarily sold as a single conventional itinerary. Its service depended upon the collection and processing of changing transport information together with algorithms for searching and presenting combinations to customers. The company adopted the Kiwi.com name in 2016 and expanded its activities internationally during the following years. In June 2019, the investment firm General Atlantic announced a strategic investment in the business, demonstrating the interest of international growth capital in a Czech-founded digital platform. The significance of this development was not that the Czech Republic invented online travel booking, which had existed

internationally for many years. Rather, the company developed a particular technological and commercial approach to joining information from different transport providers. Its growth also required customer support, partner relationships and operational systems capable of handling transactions beyond the initial scale of a start-up. When the coronavirus pandemic disrupted international travel in 2020, the company faced challenges that showed how digital innovation can remain deeply dependent upon the physical industries it serves. The case illustrates both the opportunities and the vulnerability of platform entrepreneurship within an internationally connected economy. It also shows that commercial algorithms must be assessed in relation to business processes, legal responsibilities and changing market conditions.

The expansion of technology entrepreneurship encouraged stronger links among founders, investors, universities and specialist support organisations. New companies benefited from concentrations of experienced developers and from professional networks able to provide mentoring, recruitment contacts and advice about international markets. Brno and Prague were particularly important locations because their universities and established employers provided a continuing supply of technically trained people. Incubation and acceleration programmes offered organisational support, although the contribution of any single initiative depended upon the individual firms and investment environments concerned. International finance could make it possible to expand a promising product more rapidly than revenue generated in a small national market would allow. External investment also brought pressures concerning rapid growth, commercial milestones and the distribution of control among founders and financial partners. These trade-offs were especially visible in software businesses whose value depended heavily on intellectual property, customer relationships and the work of skilled personnel. Entrepreneurs increasingly had to consider data protection, cybersecurity, contractual responsibility and the complexities of operating across several jurisdictions. The growth of a start-up community therefore involved the development of managerial and legal competences in addition to programming skills. It should not be romanticised as a succession of inevitable successes, since many experiments fail or remain commercially modest despite technically credible products.

Cloud services and data-intensive enterprise applications changed the organisation of commercial software during the decade. Instead of purchasing and maintaining every application on company premises, organisations increasingly considered arrangements in which computing and software services were provided through remotely managed infrastructure. These systems could improve scalability and simplify some aspects of deployment while creating new questions about service dependence, information security and contractual accountability. Czech firms participated in this market through software development, analytics services, system integration and specialised solutions for business users. The appearance of cloud terminology in a company's marketing materials did not establish that it had devised a novel cloud architecture or originated the underlying technologies. Scientifically significant contributions had to be identified through new computational methods, demonstrated improvements in data processing or other verifiable technical outcomes. Nevertheless, engineering work remained demanding because enterprise systems must support access controls, reliable operation, interoperability and the evolving needs of users. Data science also altered business expectations by encouraging the extraction of patterns from sales records, web activity and other operational information. These

processes required competent statistical interpretation, since a large dataset does not remove problems of bias, incomplete observation or inappropriate inference. The growing importance of cloud and analytics services therefore increased demand for specialists who could connect software design with security, mathematics and organisational practice. By 2020, such competencies had become central to the professional profile of many Czech information technology enterprises.

The labour market for computing specialists evolved alongside technological change, but its development was not a simple response to the number of new university courses. Employers required programmers, systems engineers and network administrators while also seeking expertise in cybersecurity, data analysis, embedded systems and the development of digital products. Universities in Prague, Brno, Ostrava and other cities adapted teaching and research activities to incorporate emerging technologies without abandoning fundamental mathematics and computer science. International research projects gave doctoral students opportunities to encounter methods and technical systems beyond those available within a single national institution. Experience gained through commercial software development could also feed back into university teaching when professional communities maintained active relationships. Yet rapid changes in programming frameworks and operational technologies sometimes created pressure to privilege short-term skills over conceptual depth. A balanced education needed both the ability to work with contemporary tools and the theoretical foundations necessary to evaluate unfamiliar systems critically. The demand for experienced specialists contributed to competition for workers among domestic enterprises, multinational employers and research institutions. International mobility widened opportunities for Czech graduates while raising questions about recruitment and retention in academic careers. The professional significance of the decade therefore included the emergence of new combinations of mathematical reasoning, software engineering and interdisciplinary communication. A growing innovation environment therefore remained sensitive to the quality of links between universities, investors and specialised legal expertise. Maintaining these capacities remained essential because infrastructure and investment could not substitute for the people able to use and improve them.

Digital technologies also became more closely associated with the modernisation of industrial production in the Czech Republic. Manufacturing enterprises adopted systems for managing production information, monitoring equipment and coordinating logistics across complex supplier networks. The relevance of these applications was reinforced by the country's established strengths in engineering and its connections to European automotive and machinery industries. Some improvements involved the integration of commercial software into existing operations rather than original technological invention. Other projects created opportunities for new algorithms, embedded control systems or methods for analysing data collected from industrial equipment. The distinction matters because an account of national innovation should identify precisely which intellectual and engineering contributions were developed locally. Small and medium-sized firms often faced different obstacles from larger enterprises, including limited budgets, dependence upon established machinery and insufficient specialist personnel. Introducing connected sensors and automated analysis could create cybersecurity exposures when older industrial control systems had not been designed for extensive networking. University

laboratories and demonstration environments therefore played an important role in exploring technological possibilities before widespread commercial deployment. The connection between applied informatics and Czech manufacturing became more systematic, but progress depended on careful organisational change rather than the mere adoption of fashionable terminology.

Public digital policy increasingly reflected the recognition that information technology was a component of national economic organisation and administrative capacity. Earlier electronic services, including data boxes and public administration contact points, provided an institutional foundation upon which later programmes could build. During the 2010s, debates moved beyond establishing individual electronic systems towards questions of interoperability, user access and the coordinated management of digital transformation. Government strategies framed digitisation as a way to improve public services and economic competitiveness, but practical implementation depended upon legislation, procurement and organisational redesign. The Digital Czechia agenda acquired a more prominent place in government policy during 2018 as political authorities articulated wider ambitions for electronic administration and the digital economy. In 2019, the Ministry of Industry and Trade introduced the National Artificial Intelligence Strategy of the Czech Republic, identifying research, education, business applications and regulation among its areas of concern. The strategy also expressed ambitions for international scientific cooperation and a stronger national role in research excellence. Strategic declarations should nevertheless be distinguished from scientific breakthroughs, operational public services or completed technological investments. Their historical significance lies in the priorities they articulate, the organisations they mobilise and the opportunities they may create for subsequent action. By 2020, policy discussion had become more explicit about the relationships among innovation, skills, cybersecurity and public trust. These developments were important, but they did not eliminate the uneven quality of digital services or the institutional challenges associated with public-sector transformation.

The Digital Economy and Society Index (DESI), published by the European Commission, provides one way of comparing aspects of Czech digital development with those of other EU member states. Its indicators examine dimensions such as connectivity, digital skills, the use of internet services, business adoption and electronic public services. Such measures offer valuable context, although the meaning of a country's ranking depends upon the selected indicators, their weighting and changes in methodology. A strong performance in enterprise electronic commerce, for example, does not imply equally advanced public administration or internationally leading computer science research. Conversely, a university can produce influential scientific results even when the broader society faces deficiencies in digital inclusion. The 2020 DESI reporting framework illustrates the variety of issues that had come to be associated with digital competitiveness by the end of the decade. Measuring scientific contribution requires additional evidence involving identifiable research results, peer-reviewed publications, technical artefacts and scholarly influence. Industrial performance calls for attention to products, export activity, employment, investment and the sustainability of enterprises. Public-sector development must be judged through the quality, accessibility and security of services rather than by the existence of digital portals alone. The Czech experience is

therefore most accurately understood through several complementary types of evidence rather than a single national score.

Digital inclusion and everyday internet use changed substantially between 2011 and 2020, creating a larger social environment for the information technology economy. According to the Czech Statistical Office, approximately 82 per cent of Czech households had an internet connection in 2020, while around 79 per cent possessed a computer. The same statistical overview reported that the use of internet-enabled smartphones had increased dramatically compared with 2012, reflecting the spread of mobile digital services. These figures illustrate the expansion of connectivity, although access alone does not determine the quality of digital literacy or the ability to evaluate online information. Differences between age groups and household circumstances remained important, with older people and some disadvantaged households facing greater barriers to participation. Digital technologies became increasingly relevant to banking, shopping, communication and access to information, thereby influencing the commercial opportunities available to software firms. At the same time, the growing amount of personal and behavioural data created expectations concerning privacy, security and responsible business practice. The coronavirus pandemic in 2020 intensified existing trends as schools, workplaces and public services sought ways to continue their activities remotely. Demand for reliable videoconferencing, remote access, network capacity and digital support increased sharply, placing established infrastructures under unfamiliar pressures. The experience demonstrated that digital transformation involves institutions, habits and social conditions as much as the availability of equipment. It also revealed that technological readiness could vary considerably even within a society where internet access had become common.

The pandemic provided an unusually demanding test of the research and engineering capacities accumulated during the preceding years. Academic institutions relied on research networks and collaboration systems to sustain teaching, meetings and computational work during restrictions on physical attendance. CESNET expanded videoconferencing support in 2020 as universities moved substantial parts of their educational activity online. At the Czech Technical University in Prague, CIIRC researchers developed the RP95-3D protective half-mask prototype in March 2020 with the intention of enabling distributed manufacture. The project drew upon computer-aided design, manufacturing expertise, rapid prototyping and cooperation among technical and medical specialists. It should be understood as an interdisciplinary engineering response rather than as an isolated discovery within theoretical computer science. The emergency exposed the importance of adaptable research organisations able to combine digital tools, specialist equipment and rapid communication. It also revealed weaknesses in established systems, because increased online dependence created pressures involving reliability, cybersecurity, unequal access and user support. Commercial digital companies faced divergent consequences, with some services benefiting from rising demand while others were damaged by disruptions to physical travel and trade. The year 2020 therefore cannot be described simply as an acceleration of every part of the IT industry. The sudden shift also brought questions about information accessibility and the protection of personal records into sharper public focus. It brought a complicated combination of new opportunities, operational stress and changes in the expectations placed upon digital systems.

By the end of 2020, Czech computer science and information technology had moved into a substantially different institutional and commercial environment from that of the beginning of the decade. Large-scale computing resources in Ostrava, flexible scientific cloud facilities in Brno and the expanded CESNET network formed complementary elements of a national research infrastructure. The creation of e-INFRA CZ made that complementarity more explicit, although its long-term integration remained a continuing process. Artificial intelligence and data-intensive computing had acquired stronger organisational positions through institutes, research groups and international partnerships. Cybersecurity possessed a more developed legal framework, a dedicated national authority and growing links between academic training and practical security work. Czech-founded enterprises continued to demonstrate that software developed within a relatively small economy could reach international markets and attract substantial investment. These achievements existed alongside structural weaknesses, including uneven access to digital opportunities, difficulties in retaining specialists and the challenge of financing infrastructure over extended periods. National scientific progress could not be inferred from corporate valuations alone, just as the installation of powerful machines did not by itself establish original research excellence. The decade's significance lies instead in the accumulation of mutually supporting capacities through which different forms of innovation became more likely and more sustainable. The subsequent period would build upon these capacities while introducing new demands associated with advanced artificial intelligence, computing sovereignty and increasingly complex digital security. The years 2011–2020 thus formed a distinct historical stage linking earlier post-socialist modernisation with the more integrated technological ecosystem of the 2020s.

2021–2025: Artificial Intelligence, Digital Sovereignty, Emerging Computing Technologies and the Transformation of the Czech Digital Ecosystem

The years from 2021 to 2025 represented a distinctive stage in the development of computer science and information technology in the Czech Republic, although the transition was neither uniform nor complete. Earlier investments in universities, networks, software engineering and high-performance computing provided the institutional basis for ambitions that reached beyond conventional digital modernisation. Artificial intelligence (AI) attracted particularly strong attention as advances in language models and automated analysis changed the commercial and intellectual possibilities of computing. At the same time, European discussions about strategic dependencies encouraged Czech policymakers to examine who controlled essential data, computing resources, semiconductor production and cybersecurity capabilities. The meaning of technological competitiveness consequently widened from the availability of digital services to the capacity to develop, understand and govern advanced systems. This was not a movement from an entirely national system towards an international one, because Czech information technology had already been closely integrated with foreign markets and research networks. Rather, the question became how domestic institutions could retain meaningful expertise and

decision-making capacity within global technological value chains. Research organisations confronted increasing demand for computation, while enterprises faced pressure to adopt automation without weakening reliability or public trust. Public authorities also had to reconcile ambitious digital strategies with uneven implementation, financial limitations and the practical needs of citizens. The final five years of the period therefore reveal a digital ecosystem combining genuine technical progress with unresolved structural dependencies.

The immediate background to this transformation was the coronavirus pandemic, whose effects continued to shape economic and academic life after the emergency conditions of 2020. Remote communication, electronic transactions and digital administration had become essential mechanisms for preserving organisational continuity, but emergency adoption did not automatically produce mature systems. Universities reassessed arrangements for online teaching, research collaboration and access to digital resources as they returned to a mixture of physical and remote activities. Enterprises similarly discovered that videoconferencing and cloud subscriptions represented only the visible surface of a much more demanding organisational change. Reliable digital operations required secure identities, interoperable information systems, staff training and clear responsibility for protecting data. The experience of temporary disruption also made the vulnerability of supply chains and externally hosted technological services more apparent. For researchers, computational infrastructures and dependable networks became indispensable in fields far removed from traditional computer science. For public authorities, expectations of accessible electronic services increased as citizens grew accustomed to conducting everyday activities online. Yet the ability to adopt new tools remained unequally distributed among organisations of different sizes and among people with different educational backgrounds. The years following the pandemic consequently tested whether short-term digital improvisation could be converted into stable institutions and durable technological competence. This distinction is essential because an emergency increase in digital usage should not be confused with a corresponding rise in original research or software innovation.

The most visible addition to the national computing infrastructure at the beginning of this stage was the commissioning of the Karolina supercomputer at IT4Innovations in Ostrava in 2021. The installation was supported through the European High Performance Computing Joint Undertaking (EuroHPC JU), reflecting a model in which national centres and European resources were developed together. With a theoretical peak performance of 15.7 petaflops, Karolina substantially increased the capacity available for demanding simulation, analysis and artificial intelligence workloads. Its architecture combined general-purpose processing with accelerated resources designed to handle workloads that benefit from parallel computation. When commissioned, the system achieved a prominent position in international comparisons of computational performance and energy efficiency. Such rankings provide evidence of technical scale, although they do not by themselves demonstrate the originality of research conducted on a machine. The more significant scientific question concerns the kinds of models and algorithms that researchers could execute because the computing resources became available. Czech universities and scientific institutes gained stronger opportunities to examine complex problems in materials, engineering, natural sciences and data-intensive investigation. Access to sophisticated hardware also required professional expertise in parallel programming,

scheduling, software environments and reproducible computational methods. Karolina thus represented both a major infrastructure investment and a means of strengthening the human and methodological foundations of advanced Czech computing.

The relationship between Karolina and other European resources illustrated the increasingly distributed character of scientific computation. Czech participation in the LUMI consortium provided researchers with access to a powerful supercomputing system located in Finland, supplementing domestic capacity rather than reproducing it. The underlying logic was that a medium-sized national research community benefits from selected specialisation and reliable access to shared facilities. Within Czechia, the e-INFRA CZ consortium connected the resources of CESNET, CERIT Scientific Cloud and IT4Innovations into a broader research environment. CESNET contributed communication networks, security services and data infrastructure, while CERIT Scientific Cloud supported flexible computing and experimental service provision. IT4Innovations supplied large-scale computational resources and expertise in high-performance applications. Together, these capabilities made it easier to consider the scientific workflow as an integrated sequence of data transfer, storage, computation and collaboration. The model also reduced the conceptual separation between the network engineer, the computational researcher and the domain scientist. Nevertheless, integration remained a practical task requiring common access arrangements, dependable funding, user support and security coordination. A national e-infrastructure becomes scientifically useful only when researchers can navigate it without excessive administrative or technical obstacles. The consolidation of these services during 2021–2025 therefore expressed institutional innovation as well as the purchase of more powerful equipment.

The increasing importance of artificial intelligence changed what users expected from supercomputing services. Classical numerical simulations remained indispensable, but large datasets and computational learning tasks demanded different combinations of processors, memory, storage and specialised accelerators. Training a complex model requires more than a large theoretical performance figure, because communication between computing units can become a decisive constraint. Equally important are the quality of training data, the availability of suitable software and the ability to reproduce experimental conditions. Czech research groups therefore needed expertise that crossed the older boundaries between numerical mathematics, data engineering and machine learning. Infrastructure operators responded by offering specialised environments and support for computationally intensive learning and data analysis. This shift also created opportunities for cooperation with smaller enterprises that could not reasonably build comparable systems independently. Yet shared access raised difficult questions concerning commercial confidentiality, intellectual property and allocation of scarce computing time. The value of public infrastructure depended on transparent selection procedures and scientifically defensible priorities rather than technological prestige alone. By 2025, high-performance computing was increasingly understood as part of a common enabling system for simulation, artificial intelligence and industrial research.

A further transformation occurred in September 2025 when the European quantum computer VLQ was inaugurated at IT4Innovations in Ostrava. The installation resulted from an eight-country consortium and formed part of the European effort to make emerging quantum hardware

available through recognised research institutions. Unlike conventional supercomputers, quantum processors manipulate quantum states and require specialised approaches to programming, calibration and error analysis. Their development therefore represents a new research capability rather than a direct replacement for established high-performance systems. The location of VLQ in Ostrava was institutionally significant because it brought experimental access to quantum computation into the Czech national infrastructure. Researchers could begin exploring the relationship between quantum algorithms, classical optimisation and hybrid computational workflows under realistic technical limitations. The project also provided an opportunity to train specialists whose expertise would combine theoretical computer science, mathematics, physics and software engineering. International governance was integral to the initiative, since participating countries shared scientific objectives and access arrangements. The ceremony of inauguration should not be interpreted as evidence that all proposed applications had become practically mature by 2025. Quantum advantage remains dependent upon the problem, hardware performance and the ability to manage errors. VLQ therefore symbolised the opening of a research direction whose long-term contribution still required careful experimental validation.

The growing interest in quantum computing also invited a more disciplined distinction between research promise and demonstrable technological achievement. Quantum algorithms address selected classes of problems through computational operations fundamentally different from those used by ordinary digital machines. Their potential relevance to simulation, optimisation and cryptography encouraged international investment and interdisciplinary collaboration. Nevertheless, practical benefits are constrained by qubit quality, noise, available connectivity and the substantial work required to construct useful algorithms. The presence of quantum hardware does not establish that it outperforms classical computers on commercially important tasks. Czech participation in European quantum infrastructure was consequently most appropriately understood as an investment in scientific competence and experimental access. The contribution of mathematicians and theoretical computer scientists remained particularly important because they could clarify where complexity advantages were plausible. Engineers and systems researchers had parallel responsibilities in evaluating reliability, interfaces and the costs of hybrid computation. Universities also faced the challenge of educating students without treating speculative applications as settled accomplishments. By the end of 2025, the strongest conclusion was that Czechia had joined a new European infrastructure environment for quantum research, not that a quantum computing industry had already reached maturity.

The global expansion of generative artificial intelligence after 2022 profoundly influenced the Czech research agenda and public understanding of computing. Systems able to produce fluent text, computer code, images and other content made machine learning visible to organisations that had previously regarded it as a specialised scientific technique. Large language models brought together statistical learning, massive datasets and computational architectures that require substantial processing resources. Their emergence encouraged Czech institutions to reconsider the relationship between foundational AI research and the rapid adaptation of externally developed technologies. A university laboratory could investigate model behaviour, language representation or security without having the resources to train a frontier system from

the beginning. Similarly, a company could offer a useful AI-enabled service while contributing little original knowledge to the underlying model architecture. This distinction became essential for evaluating the strength of the national innovation system. Czech language support, domain adaptation, trustworthy deployment and computational efficiency offered intellectually serious problems even when research built on international platforms. Generative systems also introduced new concerns about factual reliability, copyright, confidentiality and the reproduction of societal biases. Institutions increasingly needed to distinguish persuasive automated outputs from independently verified knowledge. The period therefore changed both the tools available to computer scientists and the standards by which their practical use had to be assessed.

The Czech academic environment responded to these pressures from a foundation of established research in computer vision, natural language processing, robotics and mathematical optimisation. Charles University, the Czech Technical University in Prague, Masaryk University and Brno University of Technology had accumulated complementary strengths rather than identical disciplinary profiles. The Czech Academy of Sciences also maintained institutes concerned with information theory, intelligent systems and related mathematical methods. Participation in the European Laboratory for Learning and Intelligent Systems (ELLIS) helped connect researchers across these institutional boundaries. The ELLIS Unit Czechia described a research agenda encompassing machine learning, language and speech technologies, trustworthy AI, cybersecurity, computer vision and applications in life sciences. Such networks supported advanced doctoral training and scholarly exchange without creating a single centralised national laboratory. The institutional significance lay in cooperation among specialists able to address the limitations of contemporary models from different perspectives. Research on formal methods, for example, could inform the verification of intelligent systems, while work on optimisation addressed the efficiency of learning. The resulting collaboration demonstrated that Czech AI research was not reducible to commercial enthusiasm for generative applications. Its long-term strength depended on identifiable research questions, independently assessable publications and the development of new researchers.

Language technology provided a particularly revealing example of the importance of national scientific traditions within a global artificial intelligence environment. Czech is a morphologically complex language whose grammatical variation creates demanding problems for automated analysis and generation. Earlier work on annotated corpora, morphological tools, dependency parsing and statistical language models supplied resources that remained valuable after the arrival of neural language systems. Researchers at Charles University and other institutions could therefore approach generative models with an established understanding of Czech linguistic structure. Investigations of speech recognition and automatic translation similarly connected computational techniques with specialised knowledge of phonetics, syntax and language use. New models offered more flexible methods for analysing texts, but their fluent output could conceal errors in morphology, terminology or factual interpretation. Evaluation in Czech was especially important when systems originally developed for more widely represented languages were introduced into public services. Linguistic resources also raised questions about the provenance of training data and the rights of creators whose work contributed to model development. The distinction between language technology as an imported service and

linguistically informed national research consequently remained crucial. Opportunities extended into public administration, education, digital archives and accessibility technologies, provided that systems were tested for the contexts in which they would operate. This field illustrated how continuity with earlier Czech scholarship could support adaptation to the newest generation of artificial intelligence.

Trustworthiness became a central scientific and political issue as artificial intelligence systems entered settings where mistakes could affect individual rights or public resources. A model that performs convincingly during a demonstration may still produce unreliable results when its input data or operating environment changes. Computer scientists therefore confronted questions of robustness, transparency, uncertainty measurement and the evaluation of failure modes. The protection of personal data required particular attention where systems processed medical information, employment records or sensitive administrative materials. Czech researchers could contribute through statistical learning theory, security analysis, formal verification and methods for explaining algorithmic decisions. The wider European Union (EU) framework also became important as the Artificial Intelligence Act entered into force in August 2024. Its risk-based regulatory approach established a common legal context for future obligations, although different provisions applied according to distinct timetables. Responsible development consequently required understanding the separation between legal compliance, technical safety and broader ethical judgement. A system may satisfy a formal requirement while remaining poorly suited to the needs of particular users. By 2025, credible innovation increasingly demanded evidence about limitations as well as demonstrations of computational capability.

Czech national policy increasingly reflected this shift from general digital modernisation towards explicit governance of advanced artificial intelligence. In July 2024, the government approved the National Artificial Intelligence Strategy of the Czech Republic 2030, updating the policy framework for a rapidly changing technological environment. The strategy was prepared by the Ministry of Industry and Trade in cooperation with public and private actors. It identified priorities involving research, education, industrial application, public services and the legal and security conditions of AI use. Its stated ambition was to help the country become a creator of advanced technologies rather than merely a purchaser of foreign systems. The objective was significant because the concentration of computing resources and frontier model development outside smaller economies could deepen technological dependence. At the same time, a national strategy should be interpreted as an expression of policy priorities, not as proof that all designated measures had been implemented. Effective realisation required university expertise, industrial demand, investment, procurement capacity and measurable arrangements for evaluating results. Research excellence, business adoption and reliable public-sector use also demanded different forms of support. The policy consequently had to balance fundamental work with practical deployment without allowing short-term enthusiasm to displace the principles of scientific scrutiny. The 2024 strategy marked an important institutional acknowledgement of this challenge within Czech technology policy.

The European framework supplied a second level of direction through the Digital Decade Policy Programme 2030 and the national roadmaps prepared under it. The Czech roadmap examined connectivity, digital skills, enterprise adoption of technology and the accessibility of electronic

public services. European evaluation created a common language for comparing progress, but comparisons required attention to how each indicator was measured. The European Commission's 2025 country report described a Czech roadmap comprising 58 measures with an indicative budget of approximately 2.26 billion euros. This represented a substantial planning commitment, although the allocation of planned expenditure could not be equated with completed projects or verified outcomes. The report also recognised growing capabilities in artificial intelligence, semiconductors and quantum technologies alongside more persistent weaknesses. European recovery and cohesion funding formed part of the wider financial environment supporting digital transformation. Such resources created opportunities for strategic investment, but they also imposed administrative demands and limited project horizons. Sustainable progress depended on domestic institutions capable of maintaining services after initial investment periods had ended. By 2025, alignment with European programmes was a defining feature of Czech technology policy, but it did not eliminate the need for critical assessment of results.

The evidence supplied by European digital indicators shows why the period cannot be represented as uninterrupted technological success. The 2025 Digital Decade assessment identified near-universal fifth-generation mobile network coverage as an important achievement. At the same time, the availability of fibre connections to premises and other very high-capacity networks remained below European averages. This distinction matters because nominal geographic mobile coverage does not guarantee the reliability, speed or affordability required by every enterprise and research institution. The report also pointed to limited digital uptake among parts of the business sector, despite the presence of internationally visible technology companies. Czechia demonstrated relatively strong basic digital skills, but the distribution of advanced expertise remained a separate policy issue. European indicators therefore revealed strengths and limitations operating simultaneously within the same economy. Nor can ambitious infrastructure announcements substitute for measured improvements in connectivity available to ordinary users. The Czech case illustrates why evaluation of digital progress must distinguish technological supply, actual uptake, institutional capacity and social outcomes.

Statistical evidence concerning enterprise adoption demonstrates the difference between the visibility of artificial intelligence and its diffusion across ordinary business activity. The Czech Statistical Office reported that 17.6 per cent of enterprises with at least ten employees used some form of artificial intelligence in 2025. The corresponding share had grown rapidly from the level recorded in 2023, but it still represented a minority of the surveyed enterprises. The same 2025 statistics recorded paid cloud services in 54.9 per cent of firms within this size group. Such figures suggest a broader base of digital service adoption than of specifically AI-enabled operations. They also reveal variation according to enterprise size, with larger organisations generally reporting greater use of sophisticated technologies. These observations should not be treated as measurements of the originality or scientific quality of the systems being used. Purchasing an external service may improve productivity without generating domestically owned software or new research. Conversely, a small specialist company can contribute highly original technological knowledge while representing only a minute share of national adoption statistics. A balanced history therefore evaluates diffusion, commercial capabilities and research

originality as related but distinct characteristics of the digital economy. The changing numbers indicate momentum while also identifying a substantial gap between the most advanced firms and the rest of the economy.

The digital transformation of public administration entered a more visible stage as authorities sought to connect online identification with practical everyday services. Developments in electronic identity and public information systems created the foundation for applications usable beyond specialist administrative settings. The eDoklady mobile application became available in January 2024, initially allowing holders of Czech identity cards to present proof of identity in selected physical interactions. Its introduction did not replace all official documents or make every government service fully digital. Rather, it demonstrated an effort to extend digital identity from online authentication into controlled face-to-face verification. The expansion of accepting organisations proceeded through successive stages during 2024, showing that interoperability requires changes within receiving institutions as well as new software for citizens. Digital administration also depended on reliable registries, suitable legal procedures and secure access to data. Public trust could be damaged if convenient interfaces concealed operational failures or uncertain responsibilities for personal information. Accessibility for citizens without suitable devices or advanced digital skills remained a necessary policy consideration. The significance of the new identity services therefore lay not simply in their technological novelty but in the reorganisation of established administrative practices.

European legal developments affected Czech digital enterprises through a combination of market rules, data protection principles and requirements for trustworthy technological services. The Artificial Intelligence Act formed one component of this evolving environment, alongside established obligations concerning privacy and information security. For a company developing software for several European markets, harmonised rules could reduce the uncertainty created by divergent national requirements. Compliance nevertheless demanded technical documentation, risk assessment and organisational procedures that were not equally easy for firms of different sizes. Smaller enterprises could encounter considerable costs when translating abstract requirements into demonstrable software controls. Public authorities faced similar challenges when purchasing complex systems whose internal behaviour they could not fully inspect. European regulation also influenced discussions of dependence on foreign cloud platforms and large model providers. A policy preference for domestic or European technology was not sufficient by itself to establish adequate performance, security or competitiveness. Researchers and public officials therefore needed evidence-based procurement and proportionate evaluation of competing systems. The interaction between market openness, regulation and strategic independence became a distinctive feature of the Czech digital debate. By 2025, technological innovation increasingly took place within a framework that treated accountability as part of the system rather than an external afterthought.

Cybersecurity remained a practical test of the country's expanding dependence on information systems. The National Cyber and Information Security Agency (NÚKIB) recorded 268 cybersecurity incidents in 2024, according to its published national reporting. This was a slight increase over the 262 incidents recorded for 2023, although the agency distinguished the volume of reports from the seriousness of their consequences. Distributed denial-of-service attacks

contributed substantially to the observed incident landscape, including campaigns associated with politically motivated groups. Ransomware and attacks on operational technology presented different kinds of danger because they could threaten data integrity and the continuity of industrial operations. The wider geopolitical environment increased attention to threats affecting public institutions and critical infrastructure. Yet incident statistics require cautious interpretation because detection practices, reporting obligations and the population of monitored organisations can change. A higher recorded number does not automatically establish an equivalent increase in the underlying rate or severity of attacks. The persistence of threats nevertheless demonstrated why cybersecurity could not be considered an optional supplement to digital development. Stronger networks, computing facilities and intelligent services enlarged the potential consequences of failures if protective arrangements did not mature alongside them.

The legislative framework for cybersecurity changed substantially in the final year of the period. The Czech Republic adopted a new Cybersecurity Act in 2025, with its principal provisions taking effect on 1 November of that year. The legislation was connected with the European effort to raise standards for network and information security across critical and important sectors. It expanded and reorganised expectations concerning regulated services, organisational safeguards and reporting responsibilities. NÚKIB issued practical guidance to help affected entities determine their obligations under the new framework. The introduction of a law, however, should not be mistaken for the instantaneous achievement of comprehensive operational compliance. Organisations required time to assess their systems, establish responsibilities, prepare documentation and make technical improvements. Transition arrangements recognised that the implementation of protective measures involves organisational as well as engineering work. The financial burden could be especially significant for institutions with ageing systems or limited specialist staff. Effective regulation also depended upon clarity, proportionate enforcement and cooperation between public authorities and service operators. By the end of 2025, the legal framework for Czech cyber resilience had entered a new stage, but many practical effects remained matters for subsequent assessment.

The debate over digital sovereignty made cybersecurity questions inseparable from international technology supply chains. A modern information system may depend upon imported processors, foreign software components, cloud hosting outside national territory and continuous updates from external providers. Such dependence does not necessarily make a system unsafe, but it complicates the identification of responsibility and possible vulnerabilities. Public institutions increasingly had to consider not only conventional technical controls but also vendor governance and the consequences of disrupted access to essential services. This issue became more visible when geopolitical tensions and international economic restrictions affected assumptions about stable technology supply. Czechia's membership of the European Union and wider security partnerships provided opportunities for cooperation on threat intelligence and common standards. Nevertheless, the practical capacity to audit software, investigate incidents and maintain skilled teams remained a domestic obligation. Research institutions could contribute through cryptography, secure architectures, verification and the study of adversarial manipulation of AI systems. Industry could contribute specialised products and services, although private commercial incentives did not always coincide with the requirements of critical

public infrastructure. Digital sovereignty should therefore be understood as the capacity to make informed technological choices and manage dependencies, rather than a promise to manufacture or design every component nationally.

Semiconductor technologies acquired greater strategic prominence because computing capability ultimately depends upon specialised physical components. Czechia entered the 2020s with industrial and engineering traditions that could contribute to European microelectronics, particularly in power semiconductor technologies. In October 2024, the government approved a National Semiconductor Strategy intended to strengthen domestic capabilities within European and global value chains. The policy was framed partly by concerns over the concentration of manufacturing capacity and the security of supplies. It addressed the relationship between industrial investment, research, training and the availability of specialised engineering labour. This was an important development for computer science because advances in computing architecture, energy efficiency and intelligent systems depend on the properties of semiconductor devices. Nevertheless, power electronics and advanced digital processors occupy different technological segments and should not be presented as interchangeable. National participation in semiconductor production does not automatically imply independence in leading-edge processor design or fabrication. The strategy therefore needs to be assessed in terms of realistic specialisation and its capacity to generate durable technological competence. The Czech objective was to strengthen selected links in a complicated international chain rather than reproduce the full semiconductor industry within national borders. Such selectivity was consistent with the economic scale and established industrial strengths of the country.

An important industrial example was the announcement in June 2024 that onsemi had selected the Czech Republic for a potential major expansion of silicon carbide production. The company described a planned multiyear investment of up to two billion United States dollars associated with its operations in Rožnov pod Radhoštěm. Silicon carbide devices have particular relevance to energy-efficient power electronics, electric vehicles and other systems requiring control of substantial electrical power. The announcement highlighted the connection between microelectronics and the wider transition towards electrification and energy-efficient technologies. It also illustrated how foreign-controlled companies can contribute to domestic industrial expertise, employment and technological capability. The value of such participation should not be diminished merely because corporate ownership is international. Equally, an announced investment should not be treated as if the full planned manufacturing capacity had already been delivered by 2025. Its subsequent significance would depend on implementation, supply-chain relationships, research activity and the training of qualified workers. The case demonstrated the attraction of Czech engineering capabilities within a global industry characterised by substantial capital requirements. It also showed why assessments of national technological achievement must distinguish realised capacity, industrial intention and domestic ownership of research results.

The commercial software sector experienced a different form of restructuring as international financing and corporate consolidation changed the conditions facing established enterprises. Czech technology companies operated in markets where investment decisions, product distribution and competition were increasingly transnational. The growth of cloud-based

applications created opportunities to scale products internationally without establishing a traditional network of local offices. At the same time, rising expectations regarding reliability, security and customer support increased the organisational demands placed upon software firms. Start-ups in enterprise software, financial technology and specialised digital services sought international customers while retaining important development capacities in Prague, Brno and other Czech centres. Their strategies depended on the availability of engineers, access to capital and the ability to understand highly competitive global markets. Success, however, could not be inferred solely from a fundraising announcement or a headline company valuation. Sustainable competitiveness required credible products, recurring demand and the ability to adapt when financial conditions changed. The European digital economy offered opportunities for cross-border operation, but companies still faced linguistic, regulatory and commercial differences across markets. Czech technological entrepreneurship in the early 2020s was consequently marked by greater international reach and increasing exposure to the disciplines of global competition. This environment made software innovation a complex interaction of technical quality, organisational competence and market judgement.

The combination of Avast with the United States company NortonLifeLock offered an especially clear illustration of changing corporate relationships. The transaction was completed on 12 September 2022, after regulatory and corporate processes that followed its earlier announcement. The combined business subsequently adopted the name Gen Digital, with corporate connections to both Prague and the United States. Avast's earlier development had demonstrated how security software originating in Czechia could achieve a worldwide customer base. The 2022 combination reflected both the recognised commercial value of that legacy and the consolidation pressures within the global cybersecurity market. Its consequences cannot be described simply as either a national triumph or a loss of technological identity. Research employment, intellectual property, product strategy and investment decisions can follow different geographical patterns after an international merger. The historical significance is clearer when corporate ownership is analysed separately from the location of specialised teams and the origin of technical knowledge. The transaction also underlined how mature Czech IT companies could become important participants in international transactions on a substantial scale. It provides an example of the opportunities and ambiguities created when national technological entrepreneurship becomes embedded in multinational corporate structures.

Digital industrial transformation formed another bridge between the specialised IT sector and the country's wider productive economy. Czech manufacturing enterprises possessed established strengths in machinery, automotive production, electrical engineering and industrial automation. The use of sensors, data platforms and computer-controlled equipment created opportunities to improve processes without entirely replacing existing industrial knowledge. Artificial intelligence could contribute to predictive maintenance, visual inspection and the analysis of production data where suitable information was available. Digital twins and advanced simulations offered methods for examining the behaviour of equipment and production systems before physical changes were undertaken. These applications drew upon cooperation among software engineers, domain specialists and researchers in control theory or applied mathematics. The practical obstacle was often less the absence of fashionable algorithms than the difficulty of

obtaining dependable data from older and heterogeneous industrial systems. Cybersecurity became especially important when production equipment was connected to wider networks. Industrial adoption therefore required careful investment in integration, workforce preparation and the evaluation of measurable outcomes. The Czech experience illustrates that advanced computing can reinforce established industrial specialisations rather than establish a completely separate economic sphere. Its significance lies in the transfer of robust computational methods into workplaces where reliability has direct economic consequences.

Human resources remained a decisive condition for the development of advanced computing throughout the period. Large infrastructure projects require not only hardware specialists but also researchers able to formulate suitable algorithms and engineers capable of supporting demanding users. Artificial intelligence added demand for expertise in mathematics, statistics, data management and the evaluation of automated systems. Cybersecurity required professionals whose work combined technical competence with an understanding of organisational risk and applicable regulation. Universities in Prague, Brno, Ostrava and other centres consequently faced pressure to update curricula while preserving fundamental disciplinary knowledge. Teaching the current generation of software tools was valuable, but it could not substitute for durable competence in algorithms, programming, logic and systems design. International recruitment and academic mobility broadened the available pool of knowledge while exposing Czech institutions to competition for experienced specialists. Industry also depended upon opportunities for continuing professional development, particularly for workers whose initial education preceded contemporary AI and cloud systems. The shortage of advanced skills could constrain both research ambition and technology adoption within smaller enterprises. By 2025, the formation and retention of competent people remained at least as important as the acquisition of another computing platform.

Digital literacy and participation presented a different educational challenge from the preparation of specialist researchers. European monitoring placed the Czech Republic in a comparatively favourable position regarding the share of people with at least basic digital skills. This achievement reflected the diffusion of digital services and changes in educational opportunities, but it did not imply equal confidence across all tasks or demographic groups. The ability to use an online service differs from understanding data protection settings or recognising persuasive misinformation. Older users, people facing accessibility barriers and those with limited resources may encounter difficulties even when aggregate national indicators appear strong. School education increasingly needed to support computational reasoning and safe digital conduct rather than simply familiarity with particular commercial devices. Teachers themselves required training and reliable educational resources if digital methods were to improve learning rather than create additional burdens. Public institutions also needed to maintain accessible routes for people who could not use a smartphone-based identity application. Gender imbalances within advanced information technology occupations presented another reason to distinguish broad literacy from the recruitment of specialists. A successful digital society therefore depends on inclusive educational policy as well as on research laboratories and profitable software companies. The Czech experience during 2021–2025 demonstrated that human capability and institutional accessibility must be evaluated together.

The environmental and financial demands of advanced computing became increasingly difficult to ignore as artificial intelligence and large-scale data processing expanded. Powerful accelerators consume electricity, require sophisticated cooling and depend upon manufacturing chains with substantial material footprints. The scientific value of a computation therefore has to be considered alongside its efficiency and the resources needed to complete it. Energy-efficient architecture, careful workload management and improved algorithms can reduce costs without assuming that every problem requires the largest available model. Supercomputing centres must also balance expensive capital purchases against the recurrent expenditure needed to operate and maintain their equipment. These considerations are especially relevant for publicly financed facilities expected to serve a broad research community over many years. The European Commission's 2025 assessment acknowledged that Czech policy had begun to address the interaction between digital development and environmental sustainability, while recognising gaps in its strategic treatment. Such findings caution against defining technological progress exclusively through capacity or throughput. A durable national computing ecosystem requires credible planning for energy, personnel, hardware replacement and the protection of research data. The emerging sustainability debate thus reinforced a wider principle that innovation is meaningful only when its technical possibilities can be maintained responsibly.

The final months of 2025 brought an additional indication of the direction envisaged for Czech computing infrastructure. In October, the EuroHPC Joint Undertaking selected the Czech AI Factory (CZAI) as part of a further expansion of European facilities devoted to artificial intelligence. The project was linked to a proposed AI-optimised supercomputer, KarolAIna, intended to build on the established Karolina infrastructure at IT4Innovations. Its announced consortium connected Ostrava with academic and research partners elsewhere in the country. The initiative aimed to support access to advanced computing, AI development and the acquisition of relevant skills by researchers and enterprises. This selection was strategically important because it treated infrastructure, expertise and business adoption as related components of a national AI environment. Nevertheless, approval in 2025 did not mean that all new facilities and services had entered operation before the end of the year. An accurate historical account must distinguish the completed Karolina system from the proposed next-generation resources associated with CZAI. The prospective value of the factory would depend on its eventual operation, accessibility and the scientific and commercial work undertaken by its users. The initiative nevertheless demonstrated the growing importance of European arrangements in defining the next phase of Czech artificial intelligence development. Its place in the 2021–2025 history is therefore that of an important approved direction for future capacity, rather than a retrospectively completed achievement.

By the end of 2025, the Czech digital ecosystem combined considerably greater computing capacity with deeper questions about technological independence and social responsibility. Investments in high-performance infrastructure and the arrival of a quantum system expanded the experimental opportunities available to scientific institutions. Artificial intelligence research was strengthened through collaboration among universities, Academy institutes and European networks. National strategies for AI and semiconductors articulated ambitions that reached beyond the adoption of imported software. At the same time, official statistics revealed

persistent differences between highly digital enterprises and the broader business population. Public digital services advanced, but issues of interoperability, accessibility and trust continued to require sustained attention. Cybersecurity regulation became more demanding as the consequences of system failure grew alongside social dependence on digital networks. International mergers demonstrated the commercial value of earlier Czech software achievements while complicating any simple account of national ownership. The period was consequently best understood as a transition towards more strategic and infrastructure-intensive computing, not as the completion of digital transformation. Czechia entered the following years with stronger research tools and more explicit technological ambitions, but the measure of future success would remain the quality of knowledge, systems and institutions created from those resources.

Part Two

Major Research Directions and Technological Achievements of Czech Computer Science, 1993–2025

Theoretical Computer Science, Mathematical Logic, Algorithms and Computational Complexity

The development of theoretical computer science in the Czech Republic after 1993 was neither an isolated national invention nor a simple consequence of expanding commercial computing. It drew upon established Czechoslovak traditions in mathematical logic, combinatorics, cybernetics and the mathematical analysis of algorithms, while entering an increasingly open international research environment. The new political framework changed institutional accountability and opportunities for scientific cooperation, but the underlying problems of computability and proof remained recognisably continuous. Researchers could investigate the limits of computation independently of whether a particular programming language or computer architecture happened to dominate the market. At the same time, the growth of information technology made questions about efficiency, verification and mathematical structure more relevant to engineers and software developers. Czech universities and institutes consequently sustained communities in which abstract theorems and practical algorithmic problems informed one another without becoming equivalent activities. Prague and Brno became especially important locations for this interaction, although theoretical research extended beyond those two cities. The period from 1993 to 2025 is therefore best understood as a sequence of intellectual developments within changing institutional and technological conditions. International publications, collaborative projects and doctoral training offer firmer evidence of those developments than vague claims about a national school achieving global leadership. This chapter examines identifiable contributions while explaining the theoretical questions that made them significant.

A distinction between computability, computational complexity and algorithm design is essential to any account of this scientific field. Computability asks whether a problem admits a mechanical method of solution under an explicitly stated model of computation. Complexity theory then investigates the resources required by such a method, often measuring running time, memory consumption or the number of computational steps. Algorithm design concerns the construction and analysis of procedures that solve particular problems under relevant constraints. These questions overlap, but an algorithm can be correct without being efficient and a problem can be decidable while remaining practically inaccessible. Mathematical logic contributes languages for expressing statements and reasoning about whether conclusions follow from assumptions. Discrete mathematics supplies structures such as graphs, finite relations and combinatorial systems on which many computational problems can be formulated. Formal verification asks whether a specified system satisfies properties represented in a suitably precise logical

language. Czech research after independence contributed to several of these interconnected domains, not to a single undifferentiated discipline called informatics.

The post-1993 institutional environment preserved research capacities housed in universities and specialised academic institutes while introducing new mechanisms of competitive support. The Faculty of Mathematics and Physics at Charles University maintained communities working on discrete mathematics, computational complexity, logic and algorithms. The Faculty of Informatics at Masaryk University provided a distinct environment for theoretical computer science, formal methods and their relationship to practical computing. Within the Czech Academy of Sciences, mathematicians and researchers concerned with computer science continued to investigate questions whose importance could not be measured by immediate industrial output. Seminar programmes, doctoral supervision and access to international journals mattered especially because theoretical progress often depends on sustained criticism of technical arguments. The founding of new academic structures did not mean that established mathematical questions had to be reformulated from the beginning. Greater mobility after 1989 permitted Czech scholars to develop joint work with colleagues based at institutions in other European countries and farther afield. Department-based doctoral seminars also trained younger researchers to formulate problems, construct proofs and analyse algorithms with the precision required by international scholarship. Such collaboration provided exposure to alternative proof methods, emerging complexity problems and new standards of peer review. The strengthening of these connections was an important condition for research, but the originality of individual results still requires examination at the level of theorems and published arguments.

Mathematical logic was one of the domains in which inherited Czech expertise remained especially productive after independence. The work of Petr Hájek illustrates how questions about formal deduction can intersect with the representation of uncertainty and imprecision. His monograph Metamathematics of Fuzzy Logic, published in 1998, presented a systematic investigation of fuzzy logic as a family of mathematically defined deductive systems. The book did not claim that informal human judgements could be made infallible by assigning them numerical degrees of truth. Instead, it developed rigorous accounts of propositional and predicate calculi in which truth values and logical connectives are governed by explicit mathematical rules. This made it possible to distinguish valid deductions from intuitive associations that merely seem plausible. Hájek's treatment also connected proof theory, algebraic semantics and questions of logical completeness. These are foundational issues, although they have potential relevance to knowledge representation and intelligent information systems. The contribution associated with Czech research lay in clarifying the formal conditions of reasoning, not in equating fuzzy logic with every commercial application labelled intelligent.

The significance of fuzzy logic becomes clearer when it is compared with ordinary classical propositional logic. Classical systems generally distinguish true propositions from false ones, whereas many-valued systems introduce a richer set of possible truth values. A richer semantics does not automatically produce an adequate theory of reasoning, because inference rules must still be specified and examined for soundness. The relation between syntactic derivations and semantic validity is consequently a central mathematical question. Hájek's 1998 treatment explored this relation in a way that permitted comparison among different formal systems rather

than reliance on one application-specific convention. Later international scholarship developed this line of research through algebraic and proof-theoretic investigations of many-valued logics. For computer scientists, the wider lesson is that representing graded evidence and proving valid consequences are distinct operations. The resulting precision allowed scholars to compare systems that might otherwise appear similar merely because they were all described as fuzzy. Some artificial intelligence systems use probabilistic models instead of fuzzy truth values, and the two approaches should not be conflated. Czech contributions to fuzzy logic are therefore best evaluated by the mathematical results and their subsequent reception within international logical research.

A different and especially demanding connection between logic and computation appears in the study of bounded arithmetic and propositional proof complexity. Jan Krajíček's 1995 monograph Bounded Arithmetic, Propositional Logic, and Complexity Theory established an extensive synthesis of logical theories and computational resource bounds. Bounded arithmetic investigates formal systems whose available methods of defining and proving statements reflect restrictions related to computational feasibility. Such systems make it possible to ask which computational principles can be justified within relatively weak theories of arithmetic. This question is not merely philosophical, because it connects the strength of proofs with classes of algorithms and the complexity of decision problems. Krajíček's research also examined propositional proof systems, where the length and structure of formal derivations become mathematical objects in their own right. The central issue is whether families of statements have efficiently constructible short proofs in a given proof system. These questions relate to major unsolved problems of computational complexity, but no celebrated open problem should be described as solved without a specific supporting theorem. Research pursued through Czech academic institutions helped establish proof complexity as a sustained bridge between mathematical logic and theoretical computer science.

Proof complexity can be understood as a study of the resources needed not just to compute answers but also to justify them formally. A logical statement may be valid even when the shortest available proof in a restricted system is extraordinarily long. Lower-bound arguments investigate why certain families of statements resist concise derivations under specified inference rules. Such results can show that a proof system has intrinsic limitations without implying the same limitation for every conceivable system. This distinction is important because the relationships among polynomial-time computation, efficient proof search and major complexity classes remain delicate. Krajíček's 2019 book Proof Complexity offers a comprehensive treatment of the subject, including upper bounds, lower bounds and connections with algorithms for propositional satisfiability. It also provides a framework for understanding feasible interpolation, a method linking proof representations to computational separation problems. A short formal proof is not the same as an efficient procedure for discovering that proof, and the difference is central to automated reasoning. For researchers designing automated reasoning tools, such results indicate why a theoretically sound calculus may still be difficult to automate efficiently. Czech scholarship in this field has thus contributed concepts by which the practical limits of formal reasoning can be investigated.

Pavel Pudlák represents another important continuity between mathematical logic, proof systems and computational complexity. His 2013 book Logical Foundations of Mathematics and Computational Complexity: A Gentle Introduction develops logical methods alongside the central questions of efficient computation. Pudlák's research on proof systems and lower bounds belongs to an international effort to identify what forms of reasoning can be represented efficiently. A proof lower bound concerns a defined formal system and must be interpreted with attention to its hypotheses and admissible inference rules. It does not automatically establish that the underlying mathematical statement is inherently difficult to prove by every possible method. The relationship between proof complexity and cryptographic assumptions introduces a further dimension because some arguments connect computational hardness with the limits of formal derivability. Such connections remain conditional where the underlying hardness assumptions have not been proved. The significance of this research lies in providing precise conceptual tools for testing the power and limitations of mathematical reasoning. It shows how abstract logic can address questions relevant to the security and reliability of computational procedures without itself becoming an engineering manual.

The emergence of younger researchers ensured that the Czech study of logic and complexity did not depend solely on established figures from earlier generations. Emil Jeřábek, educated in Prague and associated with the Institute of Mathematics of the Czech Academy of Sciences, developed research on bounded arithmetic and computational complexity. His work illustrates how weak logical theories can be connected to specific computational operations and complexity classes. The investigation of arithmetic principles sometimes reveals that a seemingly elementary operation is difficult to formalise under restrictive axiomatic assumptions. Such problems require proofs about definability, induction and the resources needed to represent computation inside mathematics. Jeřábek's publications also show how international collaboration and specialist seminars sustain technical research that receives little immediate public attention. These contributions should be assessed through their specific claims rather than by assigning them a general role in the creation of modern artificial intelligence. A documented example is his later investigation of iterated multiplication and the properties provable within restricted theories of bounded arithmetic. Their relevance to computer science arises because logical theories provide disciplined ways of expressing the capabilities and limitations of algorithms. The continued development of this line of investigation demonstrates the importance of intergenerational research communities in Czech mathematical informatics.

The connection between logic and software becomes most visible when a computational task is represented as a formal decision problem. Boolean satisfiability (SAT) asks whether truth values can be assigned to variables so that a formula is satisfied. SAT provides a common language for encoding numerous search and verification tasks, although the size and structure of the encoding can determine practical performance. A solver may discover that no satisfying assignment exists, but explaining the correctness of that conclusion requires attention to the associated proof or certificate. Proof complexity studies the theoretical difficulty of producing such justifications under different formal systems. Automated theorem proving and model checking likewise depend on sound inference rules, careful representations and appropriate decisions about the scope of a search. This relationship illustrates how abstract research can inform practical tool

design without claiming that a particular tool was invented by every theorist whose concepts it uses. Czech research in logic provides part of the intellectual background for such methods, especially where efficiency and verifiable reasoning meet. The relationship remains reciprocal, since difficult verification tasks often inspire fresh questions about the strength of proof systems.

Graph theory constitutes another particularly visible area of Czech contribution to theoretical computer science. A graph records objects as vertices and selected relationships as edges, making it a versatile language for networks, assignments and computational constraints. The mathematical interest of graphs extends far beyond their ability to represent familiar technological networks. Researchers investigate structural properties, colouring, homomorphisms, sparsity and decomposition because these features determine what can be inferred or computed efficiently. The Prague school associated with Jaroslav Nešetřil played an important role in the development of modern structural graph theory and its algorithmic connections. This work belongs to international discrete mathematics, yet its substantial association with Charles University provides a documented Czech institutional contribution. The decisive achievements are not merely individual graph algorithms but frameworks that organise large families of graphs according to mathematically meaningful properties. The Prague tradition was reinforced by specialist seminars, advanced teaching and the circulation of unresolved problems between successive generations of researchers. Such frameworks can reveal unexpected similarities among problems that otherwise look unrelated. Their lasting influence comes from enabling other researchers to ask sharper questions about computational tractability and logical definability.

A central example is the theory of graph homomorphisms developed through international work by Pavol Hell and Jaroslav Nešetřil. Their 2004 book Graphs and Homomorphisms systematically connects structural graph theory with computational questions about preserving adjacency under mappings. A graph homomorphism sends vertices of one graph to vertices of another while respecting the relations specified by edges. This apparently simple condition encompasses graph colouring and many assignment problems expressed as constraints. The existence of such a mapping may be straightforward for some target structures and computationally difficult for others. Classification therefore matters because it replaces an indiscriminate collection of examples with general questions about structural conditions. The book also considers retractions, products and composition, showing that homomorphisms form a rich algebraic and combinatorial subject. As a joint Czech–international scholarly contribution, it demonstrates how established mathematical questions can become central to theoretical computer science. Its relevance to algorithms arises from the decision problems and complexity classifications that these structures make possible.

Graph homomorphisms also provide a useful entrance to the theory of constraint satisfaction problems. In a constraint satisfaction problem, variables must be assigned values in accordance with a collection of specified relations. Graph colouring is a familiar example because neighbouring vertices may be required to receive different colours. Many scheduling, configuration and database questions admit related mathematical formulations, although an encoding does not guarantee computational efficiency. Structural and algebraic features of the allowed relations can determine whether a family of instances is tractable or computationally

hard. The study of homomorphisms thereby connects combinatorics with logic, algorithm design and computational complexity. Czech-associated work contributed to the structural language in which these questions can be examined. This shared formal language makes it possible to compare graph-theoretic results with algebraic and logical approaches to the same family of computational questions. It would be misleading, however, to treat every international classification theorem in constraint satisfaction as an exclusively Czech discovery. A historically sound account identifies the specific mathematical contributions of researchers and collaborators and distinguishes them from later results produced elsewhere.

One of the most consequential developments associated with Nešetřil and Patrice Ossona de Mendez was a systematic theory of sparsity in graphs and finite structures. Informally, sparse networks possess comparatively few local relationships, but the relevant mathematical notion depends on more than simply counting edges. Different constructions can preserve a low average density while hiding complicated substructures that frustrate efficient algorithms. The theory therefore uses structural conditions that remain meaningful under carefully chosen graph operations and decompositions. Classes of bounded expansion and related notions of nowhere-dense behaviour provide ways to distinguish structurally restricted families from unrestricted graphs. This approach draws together graph minors, neighbourhood structure, colouring properties and algorithmic decomposition. It creates a language for predicting when large inputs admit more efficient analysis than worst-case results for arbitrary graphs would suggest. The contribution is conceptual as well as technical, because it connects several previously separate measures of graph complexity. Its significance should be measured through the exact theorems and algorithmic consequences established, not through an impression that all sparse graphs are automatically easy.

The monograph Sparsity: Graphs, Structures, and Algorithms, published by Nešetřil and Ossona de Mendez in 2012, gave this research programme a systematic presentation. It treated sparse graphs as part of a broader theory of finite structures rather than as a minor special case of graph algorithms. The authors investigated decompositions, bounded expansion, homomorphism-related questions and logical preservation phenomena within a unified framework. This approach made structural properties visible at several levels, ranging from local configurations to global restrictions on classes of graphs. The book also related those properties to algorithmic questions, including cases where linear or nearly linear computational procedures become available. Such claims are always conditional on the specified graph class and computational model, rather than promises of universal efficiency. The value of the work is particularly evident where structural characterisations support new results in descriptive complexity and parameterised algorithms. Earlier papers published in 2008 had already clarified both the decomposition theory of bounded-expansion classes and some of its algorithmic consequences. It provides a documented example of research based partly in Prague influencing the language and methods of international theoretical informatics. The same achievement is best understood as a partnership between Czech and French scientific institutions, not as an exclusively national undertaking.

Structural graph theory acquired further computational significance through its connections with logical model checking. In model checking, one asks whether a formal structure satisfies a given sentence or collection of specifications. For arbitrary large structures, the computational

difficulty of this task can make apparently modest questions prohibitively expensive. Restricting the structure to a class with suitable sparsity properties can change the algorithmic situation. The key insight is that a logical formula and the graph on which it is evaluated contribute different forms of complexity. Researchers therefore analyse the interaction between the expressiveness of a logical language and the structural restrictions placed on possible inputs. The sparsity programme helped clarify how local graph configurations, decompositions and first-order definability can be exploited in algorithmic reasoning. Such theoretical results are relevant to graph databases and verification, although implementing a dependable application requires additional engineering work. The Czech contribution is strongest where a precise structural theorem or method can be traced to a scholarly publication and its later influence.

Jiří Matoušek's work shows how discrete and computational geometry formed another productive bridge between mathematics and computer science in Prague. His 2002 book Lectures on Discrete Geometry presented geometric configurations through combinatorial methods and carefully motivated applications. Problems involving convexity, incidence, arrangements and geometric transversals can be understood as questions about finite structures and the algorithms that process them. A collection of points or lines may appear easy to visualise while presenting formidable combinatorial complexity in higher dimensions. Geometric algorithms therefore require tools for bounding the number of relevant configurations and controlling computational work. Matoušek helped develop an intellectual setting in which abstract geometric arguments could inform the analysis of algorithms. The relation to computer science does not mean that every result in discrete geometry immediately becomes a practical graphics technique. His exposition also helped transmit advanced geometric methods to younger researchers, an educational contribution that complements the creation of original theorems. Its significance lies in the shared mathematical language used to investigate geometric data, search and optimisation. His publications provide a clear example of how a scholar affiliated with a Czech institution contributed to an international discipline beyond traditional boundaries between mathematics and informatics.

The algorithmic side of discrete geometry raises practical questions that are inseparable from mathematical reasoning. An algorithm may seek intersections, nearest neighbours, convex hulls or arrangements within a collection of geometric objects. The size of the input alone does not determine difficulty, because the arrangement of objects can make the number of relevant interactions very large. Randomisation, sampling and decomposition sometimes yield useful bounds, but their applicability depends on carefully stated assumptions. Theoretical analysis seeks guarantees that remain valid for whole classes of inputs rather than only for a collection of successful demonstrations. This approach has influenced fields that work with spatial data, visualisation and computational modelling, even when their practical systems use additional approximations. Czech-associated research in combinatorial geometry contributed to the development and teaching of precisely these techniques. The relationship between theorems and implementations is therefore a chain of intellectual translation rather than an automatic transfer from publication to product. Recognising this distinction allows an account of scientific innovation to value fundamental work without exaggerating its immediate industrial consequences.

A related research direction concerns the structural parameters that make otherwise difficult graph problems manageable. Tree-width measures, in a technically defined sense, how closely a graph resembles a tree from the perspective of certain decompositions. Problems that are intractable on unrestricted graphs may admit efficient methods when such a structural parameter remains small. Researchers developed additional notions, including branch-width, rank-width and clique-width, to capture different forms of manageable structure. Petr Hliněný, working at Masaryk University and other Czech research institutions, contributed to this international conversation. The survey by Hliněný, Sang-il Oum, Detlef Seese and Georg Gottlob, published in The Computer Journal in 2008, examined width parameters and their algorithmic applications. It explained how these concepts relate to dynamic programming, structural graph analysis and broader combinatorial systems. The survey distinguished among these parameters instead of treating them as interchangeable measures of an intuitively simple graph. The significance of the work is not a claim that all hard problems disappear under a suitable name. It is the identification of mathematical conditions under which specified classes of problems admit rigorous algorithmic treatment.

Parameterised complexity extends this idea by analysing the size of a problem together with a parameter that may capture structural simplicity. A procedure is called fixed-parameter tractable when its running time separates an arbitrary dependence on the parameter from a polynomial dependence on the main input size. This concept does not guarantee usefulness if the parameter is large or the hidden function grows too rapidly. It nevertheless offers a more discriminating picture than classifying every difficult problem solely by its worst-case complexity on unrestricted inputs. Graph width, the number of exceptional elements and other structural features can serve as informative parameters. Czech theoretical informatics has engaged with these questions through graph algorithms and combinatorial research in Prague, Brno and collaborating institutions. The resulting analysis helps determine which properties of real instances may justify efficient specialised methods. A parameterised theorem is valuable because its conditions and guarantees are explicit, not because it promises uniformly fast computation. Such work illustrates how structural mathematics can transform the formulation of algorithmic problems without overturning established complexity theory.

The theory of online algorithms provides a contrasting way of understanding computational difficulty. An online procedure makes decisions while information arrives progressively, without knowing the complete future sequence of requests. In scheduling, for example, a system may need to assign work to machines before later tasks have become known. An analysis compares the outcome of an online strategy with an appropriate benchmark that has access to more complete information. This produces a framework for measuring what can be achieved under uncertainty rather than simply computing an optimal solution from a finished input. Jiří Sgall, associated with Charles University, contributed to research on online scheduling, approximation methods and algorithmic complexity. His 1998 survey On-line Scheduling consolidated questions about scheduling procedures and their theoretical guarantees. Any meaningful bound consequently depends on the specified machine model and on what information is available when each decision must be taken. Subsequent work examined load balancing, machine scheduling and related decision problems, often through international collaborations. The Czech

connection is demonstrated by sustained research and teaching in Prague rather than by an assumption that online scheduling originated there.

Approximation algorithms address optimisation problems for which computing an exact optimum may be too expensive. Their objective is to obtain a feasible solution whose quality can be bounded relative to the best possible outcome. The guarantee is mathematical and depends upon how the objective and input assumptions are formulated. An attractive heuristic may perform well in practice without providing a corresponding worst-case approximation guarantee. Czech researchers working in algorithm design investigated approximation and scheduling questions within the broader international literature of theoretical computer science. Studies associated with Sgall and his collaborators show how performance bounds can be established for particular machine models and arrival patterns. Some results concern unavoidable limitations, revealing that no algorithm in a stated class can surpass a proven boundary. Others propose procedures that approach the best guarantee attainable under the model. It demonstrates why theoretical research remains relevant to software systems that allocate scarce computational resources.

Formal languages and automata theory supply yet another foundation for understanding programs and computational systems. A finite automaton represents behaviour through states and permitted transitions, providing a mathematical model for pattern recognition and certain forms of system control. More expressive models can represent recursive behaviour, parallel processes or systems whose state space is potentially unbounded. Their usefulness depends on a precise balance between what the model can express and what questions can still be decided. Model checking translates requirements into logical statements and investigates whether the system model satisfies them. Research at Masaryk University's Faculty of Informatics developed this connection between automata, temporal logic and system verification. The university's documented formal-methods projects included Antonín Kučera and collaborators working on stochastic and other complex systems. The distinction between finite and infinite state spaces is particularly consequential because it changes the types of decision procedures available to the analyst. Such activity reflects a research programme rather than a single universally applicable verification algorithm. It also illustrates how theoretical questions about decidability acquire practical importance when engineers seek guarantees about software and communication protocols.

The verification of probabilistic systems complicates the traditional distinction between correct and incorrect system behaviour. In a stochastic model, transitions may carry probabilities, so researchers often ask whether an event occurs with an acceptable likelihood. Markov chains and related decision models provide formal representations for certain kinds of uncertain behaviour. Temporal logics make it possible to express requirements involving future events, repeated conditions and the order in which actions occur. The computational task then concerns probabilities, optimisation or satisfaction of the specified formula under clearly stated assumptions. Research involving Antonín Kučera, Tomáš Brázdil and colleagues at Masaryk University investigated aspects of this mathematical landscape. An institutional project running from 2010 to 2014 explicitly addressed formal methods for analysis and verification of complex systems, including stochastic models. Later publications developed more specialised results

about probabilistic temporal logics and the analysis of infinite-state systems. Such work matters because reliability claims are meaningful only when the system model and mathematical question correspond to the intended application.

Formal verification should not be confused with ordinary software testing, although the two approaches can complement one another. Testing executes selected cases and seeks evidence that a program behaves as expected under those conditions. Verification attempts to establish properties through logical or mathematical analysis of a model or implementation. A proof may cover infinitely many possible executions under stated assumptions, but it can still fail to address behaviour omitted from the model. The correct specification of requirements is therefore as important as the sophistication of the underlying algorithm. Research on automata and temporal logic helps define what can be checked and how the cost of checking changes with model structure. Czech formal-methods groups contributed to this international field by studying precise classes of transition systems and verification problems. For concurrent or recursive systems, suitable abstractions are often essential to keep the mathematical analysis within a manageable state space. Some theoretical findings support later tool development, while others primarily explain why a verification task is undecidable or computationally expensive. A rigorous historical account should recognise both sorts of result as scientific contributions rather than valuing only deployable software.

The Prague and Brno research environments developed complementary profiles rather than reproducing identical lists of specialisations. Charles University brought together strong traditions of discrete mathematics, structural graph theory, complexity, algorithms and mathematical logic. Its researchers also collaborated with colleagues in the Mathematical Institute and across international mathematical networks. Masaryk University cultivated research in graph parameters, automata, formal verification and several related directions of theoretical informatics. Each environment operated through departments, seminars and research groups whose boundaries changed over the three decades under examination. Academic labels should therefore be treated as historical descriptions of communities rather than immutable definitions of their intellectual work. The transmission of techniques through doctoral supervision, workshops and collaborative papers was particularly important in such specialised fields. Scholars could move between universities and Academy institutes or participate in projects involving several institutions at once. This mobility makes a simple ranking of cities or organisations an inadequate substitute for examining specific research results.

International collaboration was a structural feature of many of the most influential Czech-associated theoretical contributions. Nešetřil's work with Hell and with Ossona de Mendez provides especially clear evidence of ideas developed across institutional and national boundaries. Hliněný's work with Oum, Seese and Gottlob shows a comparable pattern in the study of graph parameters. The Czech scientific contribution in such cases can be identified through authorship, research affiliation, institutional support and the intellectual content of publications. It should not be represented as exclusive ownership of a theorem that was developed jointly. At the same time, the presence of foreign collaborators does not diminish the significance of the sustained Czech research environments that made collaboration possible. European research programmes, visiting appointments and specialist conferences helped

circulate techniques and establish lasting partnerships. Shared authorship complicates institutional attribution, yet it also demonstrates the ability of Czech research groups to contribute substantively to demanding international debates. The field's international language of proofs and formal definitions allowed ideas to be compared without depending on national technological standards. This history is therefore one of participation in, and contribution to, shared theoretical problems rather than competition to claim every result for a single country.

The relationship between foundations and programming is most revealing when theoretical models are translated into verifiable computational procedures. Type systems, program logics and static analysis seek ways to reason about programs without relying exclusively on observed execution. A sound method must specify what property it guarantees, which language constructs it can analyse and what assumptions it makes about the environment. Algorithms developed for graph structures or logical formulas can become components of such analyses when the translation is mathematically justified. Conversely, the complexity of real programming languages may expose limitations in idealised models and stimulate further theoretical work. Czech research in logic, algorithms and formal verification contributes to the pool of methods from which software engineering can draw. No direct commercial outcome should be inferred merely because two fields share concepts such as graphs, proofs or automata. The meaningful connection is methodological, involving explicit abstractions, proofs of correctness and computational performance guarantees. This relationship helps explain why theoretical informatics remains important even in periods dominated by rapidly changing software platforms.

The emergence of artificial intelligence renewed attention to the older problems of logical inference, search, optimisation and computational complexity. Intelligent systems may manipulate formal knowledge, learn statistical representations or combine these approaches in different proportions. Logical reasoning can support explanation and consistency checking, but a formal derivation cannot compensate for an inadequate representation of the problem. Search algorithms depend upon the size and organisation of the space they explore, while learned models introduce additional questions about data, generalisation and uncertainty. Theoretical results in graph algorithms and proof complexity therefore provide relevant conceptual tools without directly accounting for every successful machine-learning application. Czech scientific traditions in mathematical logic and combinatorial algorithms offer a foundation for interdisciplinary dialogue about such systems. The use of fuzzy logic illustrates the importance of distinguishing degrees of truth from probabilistic confidence, which answer different questions. Historical analysis must therefore separate the original contribution of a mathematical method from the subsequent technological contexts in which that method is employed. Formal verification illustrates why claims about the reliability of an intelligent system require precise statements of what is being checked. A mature account of research development resists the temptation to relabel earlier foundational discoveries as direct inventions of contemporary generative artificial intelligence.

By 2025, theoretical computer science in Czechia combined several research traditions with distinct intellectual objectives and forms of international recognition. Mathematical logicians investigated formal derivability, weak arithmetic theories and the complexity of proofs. Graph

theorists developed structural frameworks connecting homomorphisms, sparsity, decompositions and algorithmic tractability. Researchers in combinatorial geometry examined the complexity of finite geometric configurations and the methods available for analysing them. Algorithm designers studied online decision-making, scheduling, optimisation and performance guarantees under incomplete information. Formal-methods researchers investigated automata, stochastic processes, temporal logic and mathematical verification of systems. These directions were connected by a shared concern with what can be computed, how efficiently it can be done and how correctness can be established. The Czech experience demonstrates that national scientific strength can consist in maintaining concentrated communities capable of contributing original concepts to internationally shared problems. The historical lesson of 1993–2025 is that fundamental research, interdisciplinary collaboration and rigorous mathematical argument remain indispensable elements of technological development.

Artificial Intelligence and Machine Learning: From Knowledge-Based Systems to Neural Networks and Generative Models

The development of artificial intelligence in the Czech Republic between 1993 and 2025 illustrates a transformation in both the intellectual foundations and practical ambitions of computer science. Artificial intelligence (AI) investigates computational methods through which machines can represent information, make decisions, recognise patterns, plan actions and perform tasks associated with intelligent behaviour. Machine learning (ML) constitutes an important but not exhaustive part of this field, because some intelligent systems rely principally on explicit rules and symbolic reasoning rather than statistical training. The historical movement from knowledge-based systems towards neural networks was therefore a change in methodological emphasis rather than the disappearance of earlier approaches. Czech research entered this movement with traditions in cybernetics, mathematical logic, control engineering and the design of complex technical systems. After independence, researchers acquired more opportunities for international collaboration, specialised education and participation in emerging technological markets. The resulting research landscape developed distinctive strengths in multi-agent coordination, speech technology, robotics, formal decision-making and industrial applications. During the 2010s and early 2020s, deep learning and generative models widened the range of scientific questions investigated within these traditions. A comprehensive account must identify original contributions, separate academic research from commercial implementation and avoid treating every imported software application as a national scientific invention. The Czech experience is consequently best understood as the cumulative development of several related research communities within a changing European and international environment.

The intellectual preconditions of contemporary Czech AI existed long before the country became independent in 1993. Czechoslovak mathematicians, engineers and computer scientists had

investigated automation, system modelling, classification and computational reasoning within the broader traditions of cybernetics. Such investigations were shaped by the institutional and political constraints of state socialism, yet they accumulated valuable skills in mathematical formalisation and the design of automated systems. Universities and Academy institutes sustained academic communities whose expertise could later be redirected towards emerging problems of intelligent computation. The political changes beginning in 1989 opened the possibility of more regular contact with international journals, conferences, research laboratories and technology firms. The terminology of AI itself covered several partly competing approaches, from symbolic knowledge representation to probabilistic reasoning and adaptive control. This diversity mattered because a method designed for a small expert system could not automatically be applied to a large autonomous network or a data-intensive recognition problem. Historical interpretation should therefore examine how inherited conceptual approaches were tested against new technical possibilities and institutional incentives. By the beginning of the new century, Czech research groups were increasingly participating in debates that crossed the boundaries between university computing, industrial automation and intelligent information processing.

Knowledge-based systems represented an important early paradigm because they attempted to express specialised expertise as rules, facts and relationships accessible to a computer. In a typical expert system, an inference mechanism applies rules to a structured knowledge base and produces recommendations or conclusions for a defined class of problems. The promise of this approach was its relative transparency, since an analyst could often inspect which explicit conditions supported a particular answer. Its principal weakness was the difficulty of obtaining, updating and validating the necessary knowledge when professional practice involved ambiguity or constant change. Czech researchers encountered these methodological issues through work in applied informatics, diagnostics, industrial systems and decision support. The usefulness of a rule-based system depended less on the label of intelligence than on the completeness of its representations and the reliability of its conclusions. Knowledge engineering consequently required collaboration between computer scientists and domain experts, a pattern later repeated in machine-learning projects. The movement towards statistical methods did not render explicit rules obsolete, since safety constraints and legal requirements can still demand interpretable conditions. Contemporary hybrid systems combine learned estimates with logical structures precisely because the two forms of representation address different limitations. The early expert-system tradition thus provided both technical experience and a lasting methodological concern with the intelligibility of computer-generated decisions.

Symbolic reasoning was closely connected with research on search, planning and the mathematical representation of uncertainty. A planning system describes possible actions, relevant states and desired outcomes before seeking a sequence or policy that reaches its objective. Classical planners can exploit explicit domain structure, whereas real-world applications introduce incomplete observations, changing conditions and conflicting agents. Probabilistic models offer ways to express uncertainty without assuming that every system state is known with certainty. These techniques are not interchangeable with fuzzy logic, which describes graded propositions rather than probabilities of events. Nevertheless, a theoretically

correct plan may remain impractical if its computation takes too long or if its environmental assumptions are violated. Research consequently turned towards approximate solutions, hierarchical strategies and adaptive approaches suitable for complex operating environments. The subsequent development of autonomous agents drew directly upon these questions while adding communication and coordination among multiple decision-makers. The intellectual continuity is evident in the persistence of reasoning and planning problems beneath successive generations of technical architectures.

One of the most recognisable Czech directions developed around the Prague research tradition in distributed artificial intelligence and multi-agent systems. The Agent Technology Group was established at the Czech Technical University in Prague around 2000, while the later Artificial Intelligence Center broadened the agenda towards additional forms of intelligent computation. Michal Pěchouček and colleagues contributed to the development of this research environment through work on cooperation, negotiation and distributed planning. A multi-agent system models several interacting entities, each of which may possess its own knowledge, objectives and decision-making procedures. Its scientific problem is not merely to make each entity individually competent but to explain how collective behaviour emerges under limited information and communication. Research on these questions provided a basis for investigating transport, security, industrial coordination and robotic systems. The institutional history requires careful chronology, because accounts of the current centre can retrospectively describe earlier research groups as part of one continuous organisation. In a 2017 university interview, Pěchouček identified the centre established in 2016 as a wider successor to the original agent-technology activities (Czech Technical University in Prague, 2017). This continuity of personnel and research questions demonstrates why scientific schools should not be defined solely by the date of an organisational name. The Prague example also shows how a focused research area can expand into a broader interdisciplinary programme without abandoning its original foundations.

Industrial applications gave the Czech tradition of multi-agent reasoning a distinctive technological orientation. Vladimír Mařík and colleagues investigated architectures in which autonomous components cooperate to perform manufacturing and organisational tasks. Such systems could represent production resources, orders and scheduling responsibilities as interacting decision-making units rather than as elements controlled exclusively from one central programme. The attraction of distributed coordination was its potential flexibility when machinery, priorities or production conditions changed unexpectedly. However, autonomy introduced difficulties concerning conflict resolution, communication overhead and the verification of overall system behaviour. Czech work belonged to a broader international discussion of holonic and multi-agent manufacturing, and its achievements must be read within that collaborative context. The practical significance lay in exploring how formal models of cooperation could be implemented within real industrial information systems. Engineering validation remained essential because simulations could not establish every property of an operating factory. This research connected theoretical AI with a national economy possessing long traditions of mechanical engineering, industrial electronics and automated production.

The AgentFly programme offers a concrete illustration of the translation of agent-based methods into experimentally testable systems. Researchers associated with the Czech Technical

University investigated how autonomous aircraft and air-traffic participants might plan trajectories while avoiding conflicts. Their work combined spatial search, distributed coordination, simulation and models of flight behaviour under operational constraints. AgentFly was designed to support large-scale experiments in which many interacting aircraft could be represented with sufficient detail for meaningful algorithmic comparisons. Publications by David Šišlák, Michal Pěchouček and collaborators described the architecture and its applications to collision avoidance and airspace management (Šišlák et al., 2012). This development was scientifically valuable because it provided a reusable environment for evaluating alternative planning strategies rather than only a single demonstration. The programme also illustrated the importance of distinguishing a successful simulation from certification of an operational aviation system. AgentFly Technologies was established in 2010 to commercialise research outcomes generated at the university from approximately 2005 onwards (AgentFly Technologies, n.d.). The company history therefore documents a pathway from academic investigation to technological entrepreneurship without implying that every subsequent commercial product was itself a new scientific discovery. It represents one of the clearer examples of Czech AI research generating both publishable methods and a dedicated application-oriented enterprise.

Game theory introduced another framework for analysing situations in which the success of one decision depends on the behaviour of other decision-makers. In such settings, an intelligent agent cannot choose an optimal action solely by predicting an unchanging physical environment. It must also consider competing interests, hidden information and the possibility that opponents will adapt their strategies. Research at Czech technical and university institutions connected algorithmic planning with strategic reasoning in security and competitive environments. The mathematical concepts involved include equilibrium, adversarial optimisation and the analysis of imperfect-information games. A learning algorithm may estimate an opponent's behaviour, but the reliability of such an estimate still depends on the underlying game representation. Czech participation in international work on strategic algorithms demonstrates the value of combining computer science with mathematical economics and decision theory. This research should be regarded as a specialised field of AI rather than simply a precursor to conversational software. Its relevance extends to cybersecurity, resource allocation and the evaluation of autonomous systems interacting with strategic adversaries.

A prominent international milestone associated with Czech researchers was DeepStack, a system for decision-making in heads-up no-limit poker. The research combined recursive reasoning, game decomposition and learned evaluations in a difficult setting characterised by imperfect information. Matej Moravčík, Martin Schmid, Viliam Lisý and international collaborators reported the work in a widely discussed 2017 publication (Moravčík et al., 2017). Their method illustrated how a neural network can support strategic search without independently supplying the entire decision procedure. The system's reported success against professional players was established within a specified experimental design and should not be generalised to arbitrary economic negotiations. Its importance also lay in addressing a class of problems where agents must act without knowing every relevant variable. The research team was internationally distributed, so the resulting achievement cannot accurately be described as the exclusive invention of one national institution. Nevertheless, the participation of researchers

associated with the Czech academic environment belongs within a history of Czech contributions to international AI. DeepStack exemplifies the productive relationship between formal decision theory and data-driven approximations. It also provides a counterexample to histories that equate progress in AI solely with increasing the size of neural language models.

The expansion of statistical machine learning changed the methods available to Czech research groups during the 2000s and 2010s. Instead of specifying every inference rule, researchers could train models to identify useful patterns from annotated or otherwise structured datasets. The scientific questions consequently included feature selection, generalisation, model comparison and the effects of imperfect training data. Statistical learning was especially attractive for tasks involving speech, images, signals and other observations resistant to exhaustive rule-based description. It did not eliminate the need for domain knowledge, because researchers still had to define objectives, collect suitable evidence and judge whether a model addressed the intended problem. The methodological move towards learned representations also raised practical concerns about computation, reproducibility and the documentation of experiments. Improvements measured on one dataset could be misleading when recording conditions or population characteristics changed. Researchers increasingly combined established signal-processing expertise with new optimisation methods and larger computing resources. The resulting transformation is best understood as a gradual reconfiguration of scientific practice rather than a single moment at which symbolic AI was replaced.

Speech research at Brno University of Technology became one of the most significant Czech-associated environments for data-driven AI. The Speech@FIT group developed research in speech recognition, speaker identification, language recognition and the computational analysis of audio recordings. Its university setting brought together signal processing, statistical modelling, language technologies and software engineering under a common research programme. Jan Černocký, Lukáš Burget and collaborators cultivated a research community that participated in international evaluation exercises and scientific partnerships. Reliable speech recognition presents challenges involving acoustic variability, different speakers, noisy environments and languages with uneven training resources. Earlier techniques relied heavily on probabilistic acoustic models and carefully engineered representations of audio features. The subsequent adoption of neural architectures altered how such representations could be learned from training data. The group identifies its work as contributing to the adoption of neural methods for speech and language processing (Brno University of Technology, n.d.). This record is more informative than a claim that a single university independently invented modern speech recognition. It demonstrates how cumulative methodological competence can position a regional research group to influence widely used computational approaches.

A particularly clear original contribution emerged from work on recurrent neural-network language models at Brno University of Technology. Tomáš Mikolov, Martin Karafiát, Lukáš Burget, Jan Černocký and Sanjeev Khudanpur published a study in 2010 comparing a recurrent model with established statistical language-modelling techniques (Mikolov et al., 2010). The paper investigated how a network's internal state could encode aspects of earlier word sequences when estimating the probability of subsequent words. This offered an alternative to models that conditioned predictions on a limited fixed history represented through explicit word

combinations. The reported experiments showed substantial improvements under particular evaluation conditions, although the paper also acknowledged higher training costs. Its institutional affiliations included Brno and Johns Hopkins University, an example of internationally collaborative work supported by Czech research training. The importance of the study lies in a reproducible comparison of language-modelling methods rather than in retrospective claims that it anticipated every subsequent innovation. Neural models of sequences subsequently became central to speech recognition and several branches of language technology. This contribution deserves particular attention because its technical originality and Czech institutional connection are both directly documented in the primary publication.

Tomáš Mikolov's subsequent work provides an instructive example of the international movement of researchers and ideas originating within the Czech academic environment. In 2013, he co-authored an influential publication on efficient methods for learning continuous numerical representations of words (Mikolov et al., 2013). The work proposed architectures that made it practical to estimate useful word vectors from very large text collections. Its significance concerned the representation of linguistic relationships in a form amenable to computational comparison and downstream modelling. The research was conducted at Google with international colleagues rather than at a Czech laboratory, and that affiliation is essential to accurate national attribution. Mikolov's earlier training and research activity in Brno nevertheless form a meaningful part of the intellectual history of his subsequent contributions. The development did not mean that numerical word embeddings were invented from nothing in 2013, since related ideas had an existing research history. Its particular achievement was a combination of modelling choices and computational efficiency that encouraged widespread adoption. Later transformer-based systems used different architectures while continuing the broader movement towards learned representations of language. This trajectory illustrates how Czech research environments could educate scientists whose later work influenced international AI beyond national institutional boundaries.

The growth of deep learning was associated with increasing use of multilayer neural networks for extracting complex patterns from data. Unlike earlier models that depended strongly on manually designed features, deep networks could learn several stages of representation through repeated optimisation. Czech laboratories adopted these methods in fields including audio analysis, computer vision, industrial diagnosis and biological image processing. Such adoption was scientifically meaningful when investigators developed new architectures, comparative methods, optimisation procedures or original datasets. Simply applying an existing neural network to a new software product, however, did not automatically establish an independent algorithmic breakthrough. Training procedures also required careful attention to overfitting, data leakage and the reproducibility of reported improvements. A credible research comparison had to include suitable baseline models and data partitions reflecting the intended application. The availability of open-source frameworks lowered some barriers while creating new dependencies on external software communities and computing providers. Deep learning therefore enlarged Czech research opportunities while also making scientific competitiveness more sensitive to data access and technical infrastructure.

Robotics and intelligent control further illustrate how machine learning interacts with physical decision-making. A mobile robot may use learned methods to recognise objects while relying on established optimisation algorithms to plan a safe trajectory. Real-time operation imposes demands concerning latency, reliability and recovery from unexpected events that differ from the conditions of offline training. Research at the Czech Technical University investigated planning, navigation, multi-robot systems and autonomous sensing within this broader methodological landscape. Industrial robotics also required accurate integration with mechanical systems and production software that could not be replaced by a general-purpose neural model. A successful experimental demonstration depended on the careful specification of the environment and the tasks expected from the robot. Researchers therefore compared alternative algorithms under repeatable conditions rather than treating individual demonstrations as sufficient proof of general capability. The practical value of intelligent control frequently arose from combining specialised modules whose limitations were understood. Learning-based perception widened the range of environments in which such systems could operate, but it also introduced new uncertainties into the control loop. Czech research contributed to this interaction between planning and learning through sustained work on autonomous agents and robotics.

Charles University provided another important institutional setting for the development of advanced AI methods. Its School of Computer Science supported research groups concerned with machine learning, intelligent systems, visual computing and language technologies. Such areas developed alongside fundamental work on algorithms, data structures and formal methods rather than within a completely separate technological universe. The proximity of abstract computer science to data-driven research allowed questions about efficiency and representation to interact with practical modelling problems. Artificial intelligence at the university could therefore include both theoretical inquiry and experimentation with learning algorithms. Projects involving data engineering, visual analysis and intelligent software contributed additional forms of methodological exchange. University research was also shaped by student training, doctoral supervision and international publication practices, which are not adequately measured by the number of commercial applications launched. Institutional descriptions identify several groups contributing to intelligent systems and related computational disciplines (Charles University, n.d.). The university's significance lies in the sustained production and critical testing of knowledge rather than in any single fashionable model architecture.

Masaryk University in Brno developed a notably plural research environment for AI and its applications. Its Faculty of Informatics brought together groups working on statistical learning, knowledge discovery, natural language processing, intelligent tutoring and biomedical analysis. These activities were intellectually connected but differed in their preferred methods, data types and requirements for experimental validation. Research on anomaly detection investigated how algorithms distinguish unusual observations from normal variability under imperfect information. Other groups studied how symbolic and statistical methods can be combined to improve interpretability or data efficiency. The university's AI@MUNI initiative later offered a common point of reference for researchers working across faculties and interdisciplinary programmes (Masaryk University, n.d.-a). Such coordination should not be mistaken for the simultaneous creation of all the underlying research groups. Existing expertise in modelling, databases and

computational biology created opportunities for later interdisciplinary developments. The strengths of the Brno environment therefore included both specialised research communities and the possibility of connecting them through shared infrastructure. This diversity illustrates how a national AI ecosystem can be built from several complementary traditions rather than a single dominant laboratory.

Adaptive learning provides an example in which AI research can be assessed through educational outcomes rather than technological spectacle. Radek Pelánek and colleagues at Masaryk University examined models that estimate a learner's knowledge from responses and select subsequent activities accordingly. Their research addressed student modelling, difficulty estimation, recommendation procedures and the evaluation of personalised learning environments. Unlike a conventional exercise collection, an adaptive system uses accumulated observations to change the sequence or presentation of tasks. A statistically accurate prediction of the next answer does not automatically establish that the learner has understood a concept more deeply. Pelánek's research consequently emphasised methodological choices and the difficulty of comparing adaptive systems fairly (Pelánek, 2025). Practical applications at Masaryk University included Czech-language learning tools and other educational environments developed with research input (Masaryk University, n.d.-b). The scientific value lies in the careful combination of computational models, empirical assessment and educational theory. This programme shows how Czech machine-learning research could contribute to a socially important application without being reduced to the marketing of educational software.

Medical research offered another demanding setting for machine learning because the cost of an erroneous decision can be considerable. Image analysis algorithms may assist specialists in examining pathological tissue, radiological scans or biological structures, but their outputs require appropriate validation. Czech collaborations connected computer scientists with clinicians and biomedical researchers who could formulate clinically meaningful questions. The BioMedAI TWINNING project at Masaryk University, running from late 2022 to October 2025, focused on reliable and explainable AI in biomedical applications. Its consortium involved the Masaryk Memorial Cancer Institute and partners in Graz and Berlin, illustrating the importance of cross-disciplinary and international expertise (Masaryk University, 2025a). The programme addressed reproducibility, handling of sensitive data and the interpretation of model predictions rather than treating accuracy as the only scientific criterion. Methods for cell segmentation and the analysis of digital pathology images demonstrated how technical research could support clinical workflows. Nevertheless, successful experimental results must be distinguished from routine deployment within regulated healthcare systems. Researchers also needed to address privacy, dataset variation and the possibility that a model would perform differently across hospitals. The Czech experience in this field illustrates the transition from algorithmic experimentation towards evaluation frameworks attentive to practical responsibility.

Explainable artificial intelligence emerged as an especially important research direction as increasingly complex models became difficult to interpret. Explanations may involve identifying influential input features, generating local approximations or comparing a model's output with alternative scenarios. Such techniques can help researchers detect certain errors, but an explanation that appears plausible does not necessarily establish causal validity. In medical

applications, professionals must be able to distinguish a genuine diagnostic signal from spurious correlations caused by scanning equipment or institutional practice. The RationAI research group at Masaryk University addressed explainability, model provenance and trustworthy biomedical evaluation (Masaryk University, n.d.-c). The related BioMedAI programme combined methodological development with training and collaboration between computer science and clinical communities. In October 2025, the university reported completion of the three-year project, while identifying research and organisational results rather than claiming that every proposed clinical tool had entered routine practice (Masaryk University, 2025a). This distinction is essential because scientific proof of concept, external validation and clinical authorisation represent different stages. Explainable AI therefore illustrates both the potential and the limits of turning sophisticated statistical models into accountable professional decision-support systems.

Industrial digitalisation also stimulated institutional experiments with integrated research in robotics, cybernetics and computer science. The Czech Institute of Informatics, Robotics and Cybernetics at the Czech Technical University linked advanced computing with complex industrial and engineering problems. Its work belonged to a European movement towards more flexible manufacturing, interconnected machinery and intelligent production management. Algorithms for scheduling, predictive maintenance and process monitoring require reliable integration with sensors and existing enterprise systems. These applications may employ neural networks, but the design of robust workflows also depends upon classical control theory and software engineering. The role of an interdisciplinary institute is therefore to coordinate different forms of expertise rather than to label every automated process as AI. Industrial collaboration presents further challenges associated with proprietary data, verification standards and the commercial confidentiality of results. Czech institutions sought to manage these relationships through joint projects and technology-transfer arrangements. The experience highlights a recurring feature of contemporary AI development: the value of an algorithm depends upon the institutional and engineering system in which it is used. It also makes clear why industrial application deserves analysis alongside, but separately from, the publication of original computer-science results.

National policy began to treat AI as a strategic research and economic field before generative chatbots became prominent in public debate. The Czech Republic adopted a national artificial-intelligence strategy in 2019, reflecting wider European interest in research capacity, investment and human resources. Such strategies can influence priorities and institutional cooperation, but their adoption does not by itself demonstrate achievement of their stated objectives. Research institutions continued to operate through their own scientific programmes, which could be influenced but not wholly determined by government agendas. The later strategy adopted in 2024 articulated ambitions extending towards 2030, making it necessary to distinguish goals from outcomes achieved by the end of 2025. Questions of digital sovereignty emerged because dependence on foreign infrastructure and proprietary models could constrain local research choices. Nonetheless, international participation remained indispensable to a country whose strongest AI groups developed through extensive transnational collaboration. The historical challenge was therefore to support domestic competence without confusing scientific

independence with isolation from global research. By 2025, Czech AI policy had become an important context for research development rather than a substitute for assessing publications and experimental results.

The foundation of prg.ai in 2019 represented another attempt to connect academic expertise with a wider innovation ecosystem. Academics from the Czech Technical University, Charles University and the Czech Academy of Sciences established the initiative with support from the City of Prague. Its purpose was to strengthen the visibility, collaboration and educational capacities of the Prague AI community (prg.ai, n.d.). The initiative did not replace the participating universities or create their pre-existing scientific achievements. Instead, it provided a platform for cooperation among research groups, businesses, educational organisations and public institutions. This form of coordination matters because innovative research can remain locally fragmented when institutions lack channels for exchanging expertise. Joint educational activities can also expose students and professionals to developments beyond the boundaries of their home department. From a scientific standpoint, however, the value of an ecosystem initiative must be assessed through the opportunities and results it helps generate, not merely through promotional language. The international profile of Prague increasingly depended upon attracting researchers while maintaining strong domestic training and collaboration. The initiative therefore illustrates how the social organisation of science became a distinct object of innovation policy during the later period.

The rapid spread of generative AI after 2022 changed the practical environment in which Czech researchers approached machine learning. Large language models (LLMs) could produce coherent text, assist with programming and respond to varied prompts without a separate manually programmed rule for each task. Their performance emerged from training objectives, model architectures and large datasets rather than the explicit encoding of all factual relationships. Generative systems also revealed serious limitations, including fabricated information, inconsistent reasoning and sensitivity to changes in prompts. Czech universities and research groups consequently faced new questions about evaluation, adaptation, computational cost and the safe use of existing international models. This distinction matters because connecting an externally developed model to a local application does not constitute invention of the underlying architecture. The relevance of Czech-language data made language-specific evaluation important, although a detailed investigation of computational linguistics belongs to the next specialised section. Generative AI therefore broadened national research agendas while reinforcing the need to distinguish scientific originality from technological adoption. The period also renewed interest in combining neural outputs with retrieval, verification and explicit knowledge structures.

Generative models intensified debates about what constitutes trustworthy evidence of machine intelligence. A convincing textual response can conceal factual errors, uncertain sources or training-data artefacts that are not apparent to the reader. Researchers therefore began testing models using controlled tasks, benchmark datasets and expert judgements rather than relying on isolated demonstrations. Questions about reproducibility became more difficult when important systems were provided through commercial interfaces subject to frequent changes. Czech academic teams had to decide whether to concentrate on training new models, adapting

existing systems or developing independent methods for evaluation and safety. Each approach offers different research opportunities and imposes different requirements for computing power, data and expertise. The use of generative systems in universities and public institutions also raised questions about authorship, privacy, assessment and professional accountability. Rigorous research must separate an observed improvement on a benchmark from an unsupported claim of general understanding or reliability. Hybrid methods that link generation with trusted data sources can mitigate some errors but do not eliminate the need for human validation. By 2025, critical evaluation had become as important to the responsible development of AI as the ability to demonstrate impressive model outputs.

Advanced AI research increasingly required computational infrastructure beyond that traditionally available to small university laboratories. Large datasets and complex training experiments place demands on graphics processors, network bandwidth, storage and specialised technical support. Czech participation in national and European high-performance computing networks widened the opportunities for researchers to perform computationally intensive investigations. The IT4Innovations centre in Ostrava contributed to this wider scientific environment, while collaborative infrastructure connected universities and research institutions to shared resources. Nevertheless, insufficient computational access could prevent otherwise capable groups from testing competitive models or reproducing international findings. European initiatives for AI-oriented computing therefore acquired strategic importance as research costs increased. The participation of Czech organisations in the Large Unified Modern Infrastructure (LUMI) AI Factory consortium during 2024–2025 represented an emerging route into shared European capacity (European Commission, 2025). Such initiatives should be described according to their actual approval and implementation stage at the end of the period under consideration. Computational resources became a condition shaping Czech AI possibilities, but they did not displace the intellectual importance of algorithms, data quality and specialised expertise.

The assessment of national AI achievements requires particular care because scientific careers and research collaborations regularly cross state borders. A publication by a Czech-born researcher working abroad may demonstrate the international reach of Czech education without necessarily representing an output of a Czech-funded laboratory. A paper co-authored by university scientists in Prague and foreign partners represents a collaborative result whose institutional contributions should be identified precisely. A commercially successful Czech software product may, conversely, contain applications of established international AI methods without introducing an original scientific technique. These categories overlap, but they describe different forms of contribution and should not be conflated. The careers of researchers associated with Brno speech technology and the collaborative DeepStack project make these attribution problems especially visible. They also illustrate the benefits of international mobility, shared research problems and multinational teams. Bibliometric indicators can contribute to evaluation, but citations and publication counts cannot independently establish the novelty or practical validity of a result. The decisive evidence remains the scientific content of identifiable papers, the conditions of their experiments and the influence of their methods on subsequent

work. Such an approach makes Czech contributions intelligible without reducing research history to national publicity or rankings.

The social consequences of AI application became progressively more important as intelligent systems moved into education, medicine, security and public services. Bias can arise when training data exclude relevant groups, when proxies reproduce historical inequalities or when evaluators choose inappropriate success measures. A model may also shift behaviour as working conditions change, requiring periodic assessment after deployment. Czech research communities concerned with trustworthy AI confronted these issues through explainability, formal reasoning and application-specific validation. Technical safeguards nevertheless cannot settle every ethical question, because the selection of objectives and acceptable risks remains a matter of professional and public judgement. In education, a personalised recommendation must be evaluated for its consequences for learning rather than for short-term engagement alone. In security, automated classification may create costs for individuals whose behaviour has been wrongly labelled suspicious. Research programmes capable of identifying these limitations contribute to innovation even when they do not produce a more commercially attractive model. The development of Czech AI therefore required attention to responsible governance alongside scientific and technological ambition.

Human capital remained a fundamental component of the Czech AI research system throughout the period from 1993 to 2025. Successful research groups depend on advanced mathematical education, programming competence, experimental judgement and the ability to engage critically with international literature. Universities in Prague, Brno and other centres provided doctoral training and research seminars that allowed specialised methods to circulate between generations. International exchanges could introduce unfamiliar approaches, but they also created pressures when qualified graduates found more attractive opportunities abroad. The development of local research centres and technology companies offered additional career pathways, sometimes strengthening connections between academic and commercial environments. Interdisciplinary projects required researchers capable of communicating with clinicians, engineers, linguists and other professional communities without losing methodological rigour. The availability of shared datasets, open-source software and European computing infrastructure further shaped the conditions under which younger scientists could undertake ambitious work. A national strategy concentrating exclusively on hardware investment would therefore overlook the importance of institutions that support sustained learning and scientific criticism. Equally, a strategy focused only on immediate commercial adoption would risk weakening the fundamental methods upon which future applications depend. The continuity of Czech AI research rested on this interaction between intellectual training, institutional stability and international openness.

By the end of 2025, Czech artificial-intelligence research encompassed a heterogeneous range of methods and application domains. Multi-agent planning and game-theoretic reasoning continued to provide tools for analysing distributed and strategic decision-making. Speech research and neural language modelling had contributed both domestic results and internationally influential work by researchers trained within the Czech academic environment. Computer vision, robotics and industrial optimisation connected learning algorithms with

physical and organisational systems. Educational AI showed how student models and rigorous evaluation could support adaptive instruction, while biomedical research placed particular emphasis on explanations and clinical reliability. The most valuable Czech contributions emerged where research groups identified specific problems and evaluated original solutions against clearly defined standards. Institutions and international networks enabled these contributions without making scientific quality a simple consequence of organisational size. Between 1993 and 2025, the field developed not through the replacement of reasoning by data, but through a succession of attempts to combine explicit knowledge, learning and computational decision-making. The Czech experience consequently demonstrates that durable AI innovation depends on scientific precision, interdisciplinary cooperation and the ability to assess both possibilities and limitations of intelligent systems.

Computational Linguistics, Natural Language Processing and Czech Language Technologies

The development of computational linguistics in the Czech Republic between 1993 and 2025 offers an unusually clear example of scientific innovation founded upon an existing intellectual tradition. Computational linguistics investigates how the structure, meaning and use of human language can be represented by formally specified and computationally executable methods. Natural language processing (NLP) is closely related, but its practical emphasis on analysing, transforming and generating texts or speech does not entirely coincide with the explanatory ambitions of linguistics. Language technology consequently includes corpus databases, dictionaries, parsers, automatic translators, speech systems and, increasingly, models trained on enormous collections of examples. Czech research developed at the intersection of these enterprises rather than within an exclusively engineering-oriented understanding of artificial intelligence. The language itself presents demanding problems involving inflection, relatively flexible word order, grammatical agreement and the relation between syntactic form and discourse structure. Addressing such problems requires cooperation among linguists, mathematicians, computer scientists, statisticians and specialists in digital information systems. It also requires recognising that a functioning application does not necessarily constitute a new scientific explanation of linguistic behaviour. The Czech experience is especially valuable because research groups built public linguistic datasets while developing methods capable of transfer to other languages. This chapter examines those connections through identifiable publications, research resources and institutions, with the principal chronological emphasis placed on 1993–2025.

The independent Czech Republic inherited a mature tradition of structural and mathematical approaches to language rather than constructing computational linguistics from an intellectual vacuum. Scholars associated with the Prague Linguistic Circle had long investigated functional relationships among language structures, linguistic choices and communicative contexts. After

the Second World War, research also engaged with formal grammar, mathematical linguistics and the possibilities of automated language analysis. Political constraints during state socialism shaped the institutions and international contacts through which this research could develop, but they did not eliminate theoretical originality. Petr Sgall, Eva Hajičová and Jarmila Panevová became important figures in the formal description of Czech syntax and meaning. Their work connected dependency relations with the organisation of information in sentences and with the interpretation of linguistic functions. The political opening after 1989 made it easier to place these approaches into international discussions about treebanks, computational grammar and statistical language processing. The establishment of a new state in 1993 changed institutional governance while allowing much of that scholarship to continue. The historical distinction between intellectual continuity and institutional transformation is therefore essential to understanding subsequent Czech innovations.

A distinctive foundation of the Prague school was the Functional Generative Description, a framework associated with efforts to explain the connections between grammatical structures and communicative meaning. Rather than treating words as an unordered collection of tokens, this tradition analysed how expressions enter syntactic relations and convey information across a sentence. Its conceptions of dependency, valency, topic and focus offered a rich theoretical vocabulary for later corpus annotation. In particular, valency concerns the participants and complements required or licensed by lexical predicates, making it relevant to both grammatical theory and machine understanding. Topic–focus articulation links sentence structure with what is assumed or newly communicated in a particular context. These categories provided a basis for distinguishing a representation of surface dependencies from a deeper account of linguistic relationships. Their importance did not depend on the immediate commercial success of a language product, because they offered research hypotheses that could be tested against textual evidence. Once systematically annotated corpora became feasible, the theoretical distinctions could be translated into detailed guidelines for human annotators and computational tools. This movement from linguistic models to reusable datasets exemplifies a characteristic mode of Czech technological innovation. The theoretical framework nevertheless remained open to revision when actual usage revealed ambiguity, variation or shortcomings in its descriptive categories.

Charles University's Institute of Formal and Applied Linguistics, generally known by its Czech abbreviation ÚFAL (Ústav formální a aplikované lingvistiky), emerged as a principal institutional setting for this continuity. Located within the Faculty of Mathematics and Physics, it joined linguistic scholarship to computational methods and software development. The institute's orientation made it possible to develop theoretical descriptions alongside large-scale language resources rather than treating these as unrelated activities. Researchers including Jan Hajič, Eva Hajičová, Jarmila Panevová, Zdeněk Žabokrtský and numerous collaborators contributed to different stages of this development. Their work involved morphological analysis, syntactic and semantic annotation, machine translation, linguistic databases and the design of reusable tools. The institutional significance of the research lay in the long-term accumulation of compatible methods and documented data. Collaborations with foreign laboratories provided opportunities for comparison with other linguistic traditions and technological approaches. Academic training

also ensured that new generations could work on the same resources while challenging particular decisions made by earlier researchers. The Prague school consequently became recognisable through its shared research questions and durable projects rather than through a single software invention.

Corpus linguistics created a second, complementary route by which Czech philology entered the computational era. A linguistic corpus is a deliberately assembled, digitally searchable collection of authentic language use, usually accompanied by descriptive information about its sources. In contrast to a traditional dictionary, it can reveal frequencies, collocations, grammatical distributions and patterns of variation across genres or periods. The Czech National Corpus, established within the academic environment of Charles University's Faculty of Arts, developed a substantial research programme based on such evidence. František Čermák and colleagues helped establish corpus-based approaches as a significant part of Czech linguistic investigation. The project required not merely the acquisition of texts but also policies for selection, balanced composition, annotation and scholarly access. Electronic texts contain editorial inconsistencies, duplications and metadata problems that can distort apparent patterns unless carefully addressed. Corpus construction therefore became a methodological activity with consequences for grammar, lexicography and historical linguistic interpretation. The Prague mathematical-linguistic and corpus-linguistic communities pursued partly different goals while sharing an interest in systematic and reproducible analysis. Their coexistence broadened the scientific foundations available for later language technologies.

The public release of SYN2000 in October 2000 was a formative event in the institutionalisation of Czech corpus linguistics. The Czech National Corpus documentation describes it as a reference collection of approximately one hundred million running words of written Czech. Its design attempted to represent multiple types of writing rather than simply amassing the largest conveniently available quantity of text. This distinction matters because a corpus dominated by newspapers can create misleading impressions about everyday conversation, literary style or specialist vocabulary. The dataset also encouraged the use of empirical evidence in lexicography and in discussions concerning standard and non-standard usage. Subsequent reference collections, including SYN2005, SYN2010 and SYN2015, made it possible to examine language under changing social conditions. Such resources were not identical snapshots of every register of Czech, and researchers needed to understand differences in sampling and annotation. The significance of the SYN series was therefore both scientific and infrastructural, linking sustained collection work to a wider community of users. Its contribution to modern Czech philology was measurable in the questions it enabled scholars to investigate, not simply in the number of stored words.

By 2020, the SYN series had developed into a continuing mechanism for comparing selected samples of contemporary written Czech across successive periods. SYN2020 was designed as a representative reference corpus focusing principally on texts from 2015 to 2019 and containing around one hundred million text words. Its documentation explains that the representative releases were constructed without reusing texts from preceding SYN reference corpora. This property is valuable for comparisons because the repetition of entire documents might otherwise manufacture an appearance of lexical or stylistic stability. Lemmas and morphological labels

make it possible to retrieve the different inflected forms of a word as related observations. Syntactic annotations introduce another level of interpretation by connecting words according to grammatical relations. Nevertheless, comparisons require caution because genre proportions, editorial practice and tagging decisions affect the patterns that searches reveal. Research on lexical change, phraseology and stylistic variation must therefore combine automated counts with careful linguistic interpretation. The methodological discipline of reference corpus design was therefore as important as the growth of storage capacity. The expansion of the corpus programme demonstrated how digital technology could increase empirical precision without dispensing with philological judgement.

Parallel corpora created further opportunities for exploring the particular qualities of Czech through systematic comparison with other languages. A parallel corpus aligns texts with their translations so that researchers can observe how similar meanings are expressed across distinct grammatical systems. The Czech National Corpus developed the InterCorp project to support multilingual corpus investigation, although its objectives differ from those of a training set assembled exclusively for commercial translation software. Such aligned data can illuminate Czech word order, aspect, article-less nominal expressions and the translation of culturally specific terminology. The analytical value depends upon knowing whether translated Czech has been influenced by the structure of the source language. It also depends upon maintaining bibliographic and genre metadata, because literary translation, legal drafting and subtitling involve very different constraints. The 2024 InterCorp 16ud release added cross-linguistically comparable Universal Dependencies annotation, extending contrastive research into the analysis of syntax and lexical diversity. At the same time, the apparent correspondence between sentences rarely guarantees a one-to-one correspondence between words or syntactic units. This methodological complexity helped stimulate both linguistic comparison and practical investigations of automatic alignment and translation.

The Prague Dependency Treebank (PDT) represented a particularly consequential attempt to make detailed linguistic theory usable as a computational research resource. Its development began in the 1990s and involved successive releases with increasingly elaborate annotation layers. The initial levels distinguished words and morphological information from surface syntactic dependencies between elements of a sentence. Later releases introduced a deeper, tectogrammatical representation concerned with selected semantic and syntactic relationships. This design reflected the Prague tradition's interest in the connections between observed word order and underlying linguistic structure. The project also linked annotation to valency descriptions, information structure and relations extending beyond individual sentences. According to the institute's documentation, the first public edition appeared in 2001, followed by progressively richer versions. A treebank of this kind offers more than a record of Czech grammatical patterns because it supplies examples for training and evaluating parsing systems. Its scientific contribution lies in explicit assumptions, consistent annotations and documented opportunities to test competing analytical methods. The project became an internationally visible instance of how a national linguistic tradition could inform general computational methodologies.

Preparing the Prague Dependency Treebank required the translation of theoretical distinctions into annotation procedures that different researchers could apply consistently. Morphological analysis identified grammatical categories such as case, number, gender and verbal properties. Surface dependency annotation then sought to determine how the words of an observed sentence relate to one another. These layers could not be generated reliably by assuming that the same visible sequence always conveyed the same syntactic or communicative meaning. Annotation manuals, software support and quality-control procedures therefore formed essential parts of the research achievement. Human annotators had to resolve ambiguous examples while recording distinctions that remained useful for computational training. The project also encouraged careful discussion of disagreements rather than hiding interpretative uncertainty behind an apparently exact digital label. This attention to methodological transparency explains why richly annotated corpora can remain useful across several generations of machine-learning techniques. Their long-term value is connected as much with explicable data creation as with the algorithms subsequently trained on the data.

The scientific interpretation of the treebank expanded as researchers investigated relationships that cannot be understood within a single sentence. Coreference concerns expressions that refer to the same entity, whereas bridging relations connect related but not necessarily identical referents. Discourse relations concern such connections as contrast, explanation, consequence and elaboration between portions of text. Prague research groups developed annotation schemes and tools for studying these phenomena in addition to ordinary morphological and syntactic structures. The Prague Discourse Treebank and related resources extended the earlier sentence-centred framework towards connected textual meaning. This transition matters because a reader normally interprets pronouns, references and argumentation through previous discourse rather than through a sentence considered in isolation. Work associated with Eva Hajičová, Jiří Mírovský, Anna Nedoluzhko and colleagues therefore contributed to wider debates about the computational representation of coherence. The approach also revealed how difficult it is to separate conventionally grammatical evidence from pragmatic assumptions about a communicative situation. Such research has implications for information retrieval, summarisation and the analysis of longer texts. It illustrates an original scientific contribution whose significance is not reducible to the accuracy of an individual software tool.

Valency research supplied another bridge between traditional Czech linguistics and computer-readable lexical information. A verb does not merely possess a dictionary meaning, because different senses can impose distinct expectations about subjects, objects and other complements. Czech predicates display complex patterns of case government and alternation that are important for parsing and machine translation. The PDT-Vallex resource developed valency annotations in conjunction with the Prague Dependency Treebank, making lexical requirements accessible to corpus-based study. Work on such lexicons demanded the systematic separation of lexical meaning from particular surface realisations. Annotation was therefore dependent upon theoretical analysis as well as evidence drawn from authentic sentences. Consistent descriptions of these relations could help systems identify predicate arguments and reduce certain syntactic ambiguities. At the same time, incomplete lexicons and borderline examples demonstrated the limitations of strictly rule-based accounts. The Czech

experience showed how lexical resources can serve linguistic explanation and computational interpretation simultaneously.

The VALLEX project developed a related but distinct manually edited lexicon of Czech verb valency. Its researchers, including Markéta Lopatková, Zdeněk Žabokrtský and Václava Kettnerová, connected linguistic theory with a structured inventory of verb senses and their frames. VALLEX entries were designed to describe individual lexical units rather than treating every occurrence of a written verb as semantically identical. Information about complements, grammatical forms and examples made the lexicon suitable for both language research and computational use. Its distribution in machine-readable formats, including extensible markup language (XML), also reflected the importance of interoperable linguistic resources. A printed version of VALLEX 2.5 was issued by Karolinum in 2008, illustrating the parallel existence of scholarly reference publishing and digital data provision. The project emphasised the painstaking labour of manual lexical analysis rather than presenting automatic extraction as a complete substitute for expert judgement. Its significance for language technology lies partly in facilitating the training or testing of systems intended to interpret syntactic relations. The sustained manual effort also supplied carefully analysed examples against which computational classifications could be tested. For Czech philology, the lexicon provided a formally organised perspective on longstanding questions of grammatical government and lexical meaning.

Czech morphology presented a demanding research problem because the grammatical function of a word often depends upon a relatively rich set of inflectional features. Nouns and adjectives vary according to categories including case, number and gender, while verbs carry information concerning person, tense and other distinctions. The same written word form may therefore correspond to several analyses, depending upon the surrounding sentence. Conversely, different observed forms may belong to a single dictionary lemma, a relationship that is indispensable for effective corpus search. Jan Hajič's research on computational morphology, including his 2004 monograph on the disambiguation of rich inflection, helped establish a systematic account of these difficulties. These requirements made Czech a useful test case for models handling languages with more extensive inflection than English. An apparent improvement in tagging accuracy nevertheless had to be assessed against the annotation conventions and genres used for testing. The resulting methodologies linked language-specific descriptive knowledge to general questions about statistical classification and ambiguity resolution. This combination became a characteristic strength of Prague language technology research.

The development of MorphoDiTa provided a visible example of how linguistic resources could be converted into widely reusable computational tools. Researchers Jana Straková, Milan Straka and Jan Hajič documented open-source components for morphology, lemmatisation, part-of-speech tagging and named-entity recognition in a 2014 conference publication. MorphoDiTa combined linguistic models with interfaces that could be incorporated into research pipelines and practical applications. Its usefulness depended upon the connection between trained statistical methods and curated morphological dictionaries. The MorfFlex dictionary family supplied structured information on Czech word forms and associated grammatical analyses. Such resources enabled users to move from raw texts towards searchable lemmas and grammatical categories with much less manual labour. Nevertheless, automatic analysis

remained probabilistic or rule-constrained rather than infallible, particularly with proper names, unfamiliar vocabulary and historical spellings. The release of documented software encouraged reproducibility because other investigators could run comparable procedures on different datasets. The innovation was therefore not simply an increase in processing speed but a change in the accessibility of linguistically informed analysis. This balance between scientific description and usable engineering distinguished Czech contributions to morphological technology.

The development of multilingual annotation standards created opportunities to test whether insights from Czech linguistics could be expressed in forms intelligible across language boundaries. Universal Dependencies (UD) established a shared framework for describing selected morphological and syntactic features in many languages. The project's international nature meant that Czech researchers participated in collaborative standardisation rather than owning the resulting framework exclusively. Such work forced investigators to distinguish genuinely cross-linguistic grammatical relations from categories shaped by one national descriptive tradition. Czech morphology and flexible word order made it an instructive case for assessing the portability of general dependency schemes. At the same time, a universal representation necessarily abstracts away from some distinctions captured by more elaborate Prague annotation layers. The coexistence of the two perspectives is scientifically productive because a local framework can preserve descriptive richness while a common framework supports comparison. These developments also enabled the creation of multilingual parsing systems and training benchmarks. They demonstrate how a national research school can influence international research without abandoning its specific theoretical inheritance.

UDPipe, developed by Milan Straka, Jan Hajič and Jana Straková, turned this standardisation into a practical sequence of language-processing operations. The researchers' 2016 paper described a trainable pipeline performing tokenisation, morphological analysis, part-of-speech tagging and dependency parsing. Rather than expecting users to operate several incompatible programmes, the system provided linked stages that could process texts in standard formats. Models based upon Universal Dependencies datasets made the software applicable beyond the Czech language. This wider applicability is important evidence of methodological transfer from locally developed expertise into international computational practice. Researchers could use the system to prepare input data for subsequent statistical analyses, language applications and comparisons between corpora. Yet errors at an early stage might propagate into later representations, so overall performance depended upon the quality of each component. Publication of models, evaluation results and training procedures made these limitations open to scrutiny. The relationship between UDPipe and the Prague Dependency Treebank also shows how deeply annotated data can support subsequent generations of more general tools. Czech innovation here involved the combined production of algorithms, linguistic resources and reproducible software infrastructure.

Recognition of named entities developed alongside morphology and parsing because identifying a word's grammatical category does not determine whether it denotes a person, place or organisation. Named-entity recognition (NER) requires a system to identify the span of an expression and assign an appropriate category. The Czech Named Entity Corpus (CNEC) supplied annotated examples and evaluation procedures for this task. Its second major edition contained

8,993 sentences and 35,220 manually annotated entities, according to the project documentation. For example, a geographical expression can contain another named geographical feature, while a person's full name may contain several components. The Prague research groups also developed the NameTag software family, linking corpus annotation to trainable recognition methods. Such systems are relevant to bibliographic indexing, digital archives and the detection of references in large document collections. Their limitations are visible when institutions change names or when an expression has different meanings in different contexts. The resulting research illustrates how apparently modest tagging problems can require careful linguistic modelling and sophisticated evaluation.

Semantic and discourse analysis added questions that a list of names or grammatical labels could not resolve. A system may recognise a person's name correctly yet fail to determine whether two separate mentions refer to the same individual. Likewise, a pair of adjacent clauses may express an explanation, contrast or sequence without signalling the relation through an obvious conjunction. Prague researchers developed resources that record coreference, bridging references and discourse relations in richly annotated texts. Such projects required distinctions between linguistic cues, inferred semantic relations and contextual knowledge not explicitly present in the sentence. Their annotations also made disagreement between trained researchers a methodological issue rather than a purely clerical defect. The resulting corpora can support experiments in long-document analysis, reference resolution and automated summarisation. They are particularly relevant to academic and literary texts, where an argument or narrative develops over numerous sentences. However, annotation schemes developed for contemporary prose cannot always be applied unchanged to poetry, dialogue or historically distant sources. Czech discourse research therefore highlights both the power and the limits of formalising textual understanding.

Machine translation offered a different setting in which computational descriptions of Czech confronted direct practical demands. Early statistical systems attempted to infer translation correspondences from bilingual examples rather than relying solely on hand-written transfer rules. Their effectiveness depended on the availability of parallel sentences, linguistic preprocessing and carefully designed evaluation procedures. Czech research on translation explored representations that could exploit the language's morphology and dependency structures. This work required attention to asymmetric grammatical categories because an English expression may not specify case or gender in the way a Czech translation must. Word alignment could provide statistical clues, yet a sentence-level translation rarely consisted of a series of independent word substitutions. Researchers therefore investigated more sophisticated methods for relating forms and meanings across language pairs. The field also created practical incentives for building larger and better-documented bilingual datasets. Its historical development shows why translation quality should be judged through linguistic adequacy and human use as well as through automatic scores.

The CzEng corpus family became a major resource for systematic research on Czech–English machine translation. Compiled at the Institute of Formal and Applied Linguistics, its successive versions expanded the volume and organisation of bilingual sentence pairs. Some releases also included automatically produced morphological and syntactic descriptions intended to support

experiments using linguistic structure. By 2020, CzEng 2.0 incorporated authentic and synthetically generated parallel material together with filtering and quality indicators. The inclusion of synthetic translations increased the available training material while also creating risks associated with automatically produced errors. Its project documentation distinguishes the origin of sentence pairs rather than presenting all sources as equally reliable examples of translation. This transparency matters because training data can contain misleading correspondences, repeated material and language-specific biases. CzEng helped investigators undertake comparable experiments in statistical and neural translation, including shared international evaluations. The resource also demonstrates why the ownership, licensing and documented provenance of text collections are scientific matters rather than peripheral administrative details. For Czech language research, the corpus offered a substantial empirical basis for investigating how linguistic differences affect translation technologies.

The transition to neural machine translation during the late 2010s changed the relationship between explicit linguistic analysis and learned representations. Neural models increasingly estimated translations from large quantities of paired examples through parameterised architectures rather than constructing every grammatical relation by hand. Transformer-based systems subsequently became important because attention mechanisms supported the modelling of contextual relationships at scale. Prague researchers, including Martin Popel and collaborators, participated in international evaluations of English–Czech translation with systems trained on extensive parallel datasets. Their work investigated questions of training scale, synthetic data, sentence boundaries and document context rather than treating the adoption of a fashionable architecture as an achievement in itself. Translation across sentences is especially difficult because pronouns, reference and terminological choices may depend upon previous material. Document-level experiments therefore connected neural engineering with longstanding linguistic questions about coherence. These achievements were collaborative and should not be misrepresented as the invention of neural machine translation within Czechia. Their national significance lay in the ability of Czech groups to develop competitive systems and to contribute reusable evaluation and data methodologies.

Speech research represented a complementary but institutionally distinct development in the national language-technology landscape. At Brno University of Technology, the Speech@FIT group developed expertise in automatic speech recognition, speaker identification, language identification and searching spoken recordings. Researchers including Jan Černocký, Lukáš Burget, Pavel Matějka and their collaborators linked speech signal analysis with statistical modelling and later neural techniques. Unlike written-text parsing, speech recognition must first contend with acoustic variation, overlapping speakers, environmental noise and the absence of explicit word boundaries. Czech poses additional challenges because spontaneous pronunciation, reductions and inflected word forms complicate transcription. The research group's international projects exposed its methods to demanding evaluation datasets and to multilingual conditions. Academic publications and released software demonstrated that work in Brno contributed to international speech-technology development rather than serving only a domestic market. The group's scientific trajectory also connected university training with industrial applications and international partnerships. Speech technology thereby became one

of the areas where Czech computer science moved visibly between fundamental methodology and practical deployment. Its evolution must nevertheless be assessed independently from the quite different research traditions of the Prague dependency and corpus schools.

Language and speaker identification demonstrate how specialised speech tasks generated original research questions in Brno. A language identification system attempts to infer which language is being spoken from an observed acoustic signal or a representation derived from it. Researchers combined acoustic features with phonotactic information concerning likely sequences of speech sounds. Work presented by Pavel Matějka, Lukáš Burget, Petr Schwarz and Jan Černocký in 2006 described the university's participation in a major international language-recognition evaluation. Such experiments required models capable of performing across speakers, recording conditions and languages rather than memorising a small collection of samples. These technologies can support media monitoring, the analysis of recorded interviews and the investigation of oral-language use. Their scientific importance includes evaluation design, model robustness and the interpretation of errors under changing conditions. The record of Brno research shows that acoustic language technology could achieve international visibility through expertise developed within a Czech university. It also illustrates why speech-processing success cannot simply be inferred from the performance of written-language systems.

Digital lexicography introduced another form of cooperation between computer scientists and specialists in Czech language scholarship. Traditional dictionaries seek to organise meanings, forms and examples for human readers, whereas computational lexicons additionally require consistent formal structures for machine processing. Resources such as MorfFlex, VALLEX and the valency dictionaries connected with Prague treebanks addressed different aspects of this problem. The use of structured entries enabled systematic retrieval, cross-referencing and potential integration with parsing or translation software. Yet a computational dictionary should not be mistaken for an official authority on correct usage merely because its contents are formally encoded. Its categories reflect editorial decisions, corpus evidence and particular research purposes that may differ from those of normative lexicography. Researchers therefore needed to distinguish descriptive linguistic data from standard-setting judgments about language. Digital resources could also support the study of neologisms, terminology, derivation and the relationships among inflected or related words. The resulting lexicographic infrastructure helped connect academic philology to technologies used by researchers and developers. Its durability depends upon documentation, editorial revision and clear licensing as much as upon the format of the underlying database.

The digitisation of Czech literary and historical texts opened research possibilities that extend beyond routine search or electronic reading. Scholars can use language technology to investigate lexical development, stylistic distributions, named entities and recurring expressions across large textual collections. A corpus of fiction, for example, may reveal patterns that are difficult to recognise through selective close reading of a few canonical works. Automated analysis can also support comparison among periods, genres, translations and editorial versions. Nevertheless, the meaning of a literary device depends upon historical context, genre conventions and aesthetic organisation, none of which can be recovered from frequency counts alone. The distinction between a digitised facsimile, a corrected electronic text and a linguistically

annotated corpus is therefore crucial. In Czech digital humanities, initiatives connected with computational literary studies encouraged exchange between language-resource specialists and researchers examining cultural materials. The methodological achievement lies in combining scale and reproducibility with interpretative approaches capable of questioning the results of automated classification. Such work illustrates how technological innovation can expand the evidence available to literary scholarship without displacing its central critical methods.

The provision of reliable research infrastructure became increasingly important as linguistic projects produced large and interdependent datasets. Individual university repositories could not always ensure permanent preservation, stable identifiers, consistent licences and convenient access to linguistic software. LINDAT/CLARIN (a Czech centre within the Common Language Resources and Technology Infrastructure network) emerged as a Czech language-research infrastructure connected with wider European cooperation in sharing language resources. Its later development within LINDAT/CLARIAH-CZ (Language Resources and Digital Arts and Humanities Research Infrastructure) joined linguistic data services to additional digital arts and humanities research activities. Charles University's Institute of Formal and Applied Linguistics has played an important role in these arrangements. The infrastructure provides mechanisms for depositing datasets, documenting their contents and giving researchers access to language-processing tools. Participation in international initiatives makes Czech resources more discoverable to investigators who do not belong to the original producing institution. This openness also helps research groups verify findings, reuse annotations and compare new systems with earlier results. Nevertheless, access conditions remain dependent upon copyright, personal-data restrictions and licences governing source texts and derived models. The lasting achievement is therefore a research environment in which linguistic information is treated as a maintainable scholarly resource rather than a disposable accompaniment to one project.

During the early 2020s, transformer-based language models altered the balance between carefully engineered linguistic features and broad statistical pretraining. Models learned useful representations from large corpora, while specialised fine-tuning could adapt them to tagging, entity recognition, translation and text classification. Czech researchers participated in these developments through new models, improved evaluation methods and the continued maintenance of annotated datasets. A system that achieves strong scores on an established benchmark may nevertheless fail on legal documents, historical writing or non-standard Czech if those varieties were poorly represented during training. These limitations renewed interest in the relation between corpus quality, linguistic interpretation and trustworthy deployment. For a language with fewer commercially available training resources than English, the selection and documentation of Czech data remained particularly consequential. Multilingual models offered opportunities for knowledge transfer, but could also reproduce inequalities between extensively represented and less well represented languages. Czech computational linguistics therefore entered the generative-model period with both advanced neural methods and a substantial inherited infrastructure for examining language carefully. By 2025, these approaches were best regarded as complementary rather than mutually exclusive research traditions.

Scientific assessment of Czech language technologies requires careful separation of data creation, methodological novelty, engineering implementation and commercial adoption. A

newly annotated corpus can be an original research contribution when its categories, reliability and empirical coverage enable genuinely new investigation. A reusable software tool can contribute through algorithmic design, efficiency, openness and reproducible performance rather than through the number of products that incorporate it. A translation or speech system must be evaluated against clearly defined tasks and comparable datasets, with human assessment remaining important where meaning is difficult to formalise. Institutional affiliations must also be interpreted carefully because projects such as Universal Dependencies and international translation evaluations arise from multinational cooperation. Publication records should identify which results were produced within Czech organisations and which involved Czech-born scholars employed elsewhere. The longevity of language resources introduces another measure of value, since well-documented corpora may support research long after their original funding has ended. Public accessibility must be balanced against copyright, confidentiality and the responsible treatment of potentially sensitive linguistic material. Training competent researchers remains equally important because complex annotation conventions and evaluation choices require accumulated specialist judgement. A credible national history consequently examines the quality of intellectual contributions rather than presenting every application of language software as an independent breakthrough.

Between 1993 and 2025, Czech computational linguistics developed through the sustained interaction of theoretical inheritance, empirical documentation and methodological change. Prague research preserved and extended the traditions of dependency grammar, information structure and valency through treebanks, lexicons and language-processing tools. The Czech National Corpus supplied a complementary foundation for evidence-based investigation of authentic language use across written genres and periods. Translation research transformed bilingual datasets into internationally useful experimental resources, while Brno speech groups developed distinctive expertise in spoken-language technologies. Neural learning and large language models subsequently widened the range of computational tasks without eliminating questions about grammatical structure and textual meaning. The most convincing achievements were those supported by documented resources, identifiable publications and explicit evaluation procedures. The national specificity of Czech language research lies partly in its response to the grammatical and cultural characteristics of Czech, but its international relevance rests on methods transferable beyond one language. Its development also demonstrates that digital analysis can strengthen philology and literary investigation when computational results remain subject to critical interpretation. Contemporary Czech language technology thus illustrates how a scholarly tradition can become an internationally connected scientific and technological ecosystem through cumulative, verifiable innovation.

Cybersecurity, Cryptography, Data Protection and Trustworthy Information Systems

The development of cybersecurity in the Czech Republic between 1993 and 2025 illustrates how computer science came to address not merely the production of reliable computations but also the protection of information against deliberate interference. The country inherited mathematical traditions, engineering expertise and specialised knowledge of communication systems from Czechoslovakia, yet the new security environment arose within increasingly open digital networks. Academic networks, commercial software markets, electronic banking and public information systems progressively introduced different forms of technical dependency. A computer programme could function correctly under ordinary conditions while remaining vulnerable to unauthorised access, malicious input or manipulation of its operating environment. Security research therefore required the combination of mathematical reasoning, experimental analysis, software engineering and an understanding of adversarial behaviour. Its subject matter was wider than the development of antivirus products, even though those products became internationally associated with Czech technological entrepreneurship. Cryptographic guarantees, network observability, trustworthy hardware, incident response and personal-data protection each raised distinct scientific questions. The methodological task is to identify demonstrable contributions produced in Czech institutions while recognising the international origin of many standards and widely deployed techniques. The development of these competencies also depended upon sustained cooperation between universities, research networks, public authorities and private enterprises. By 2025, Czech cybersecurity had become an interdisciplinary research environment in which fundamental results and operational experience continuously informed one another.

One starting point is the distinction between information security and cybersecurity, terms frequently treated as interchangeable in public discussion. Information security concerns the confidentiality, integrity and availability of information across digital and non-digital forms. Cybersecurity concentrates more specifically upon networked information systems, connected devices and the services they support. Cryptography supplies mathematical instruments for protecting messages and proving selected properties of information, but cannot by itself ensure that an entire service remains safe. An implementation may reveal secrets through its timing behaviour, while a perfectly encrypted database can still be compromised through stolen access credentials. Conversely, a well-managed network may resist routine attacks yet lack convincing guarantees about the cryptographic algorithms on which its authentication depends. Czech research communities increasingly investigated these different layers rather than assuming that one protective product could resolve every weakness. Their methodological diversity helps explain why discoveries about hardware keys, analysis of malicious traffic and protection of personal identities all belong within the same historical account. The purpose of this chapter is therefore to examine their connections without collapsing their distinct research questions into a generic narrative of digital modernisation.

The national research and education network offered an especially important setting for security work as Internet connectivity spread. CESNET, the Czech national research networking

association, was established in 1996 and subsequently developed services linking universities and the Czech Academy of Sciences. An academic backbone requires protection because a failure or compromise can affect laboratories, university services and shared scientific resources across institutional borders. Traffic engineering and security engineering therefore became closely connected problems rather than wholly separate administrative tasks. According to the association's historical milestones, the CESNET-CERTS security team was established in 2004, creating an organised capability for security incident handling. The team complemented network operation through responses to abuse, vulnerabilities and incidents affecting connected organisations. This work also created opportunities to study patterns of abnormal behaviour observable across networks rather than inside a single machine. Collaboration among network operators made it possible to compare incidents and refine techniques for detecting suspicious traffic without unnecessarily exposing private communications. The Czech academic-network experience illustrates the importance of long-term operational datasets and specialised professional communities for applied security research. It also underscores the difference between maintaining a useful national infrastructure and claiming the invention of the security standards employed within it.

Network security research increasingly confronted the problem of extracting actionable evidence from flows of communication too numerous for manual inspection. Packet-level analysis can provide rich detail, but comprehensive collection is expensive and may expose information unrelated to the immediate investigation. Flow records instead summarise properties such as communicating endpoints, timing, protocols and exchanged volumes. Their statistical analysis can reveal scanning, unusual communication concentrations and other patterns warranting further investigation. The scientific difficulty lies in distinguishing an attack from legitimate traffic that happens to display unfamiliar characteristics. Researchers must evaluate false alarms, missed detections and the impact of changing network conditions on previously successful methods. Their contributions are properly evaluated through identifiable measurement methods, software artefacts, datasets and peer-reviewed results rather than through broad assertions of national superiority. Reliable network defence also requires mechanisms for coordinating interpretations among institutions receiving different fragments of the same event. This movement from local packet inspection towards evidence-based network situational awareness became an important feature of Czech security expertise.

Cryptographic research developed through a different intellectual pathway because its strongest claims depend upon precise assumptions and mathematical proof. Modern public-key cryptography uses computational problems to support signatures, key establishment and authentication between parties who do not previously share a secret. The Rivest–Shamir–Adleman (RSA) cryptosystem, for example, relies upon properties of modular arithmetic and the practical difficulty of factoring appropriately generated large integers. A mathematical description of RSA is not, however, a certificate that every device implementing the algorithm produces secure keys. Real systems must select random values, store secret parameters, resist hostile observation and implement calculations without revealing unintended information. Each of these steps introduces engineering choices that can undermine an otherwise established security argument. Research groups at Masaryk University in Brno consequently examined not

only formal cryptographic properties but also the behaviour of smart cards and specialised security hardware. The Centre for Research on Cryptography and Security (CRoCS) has documented work on authentication protocols, token security, random-number generation and implementation weaknesses. This programme is distinctive because it treats the physical and software realisation of a cryptosystem as an object of experimental investigation rather than a transparent application of mathematical theory. Its achievements require the same critical scrutiny as any other empirical science, including reproducible tests and carefully qualified conclusions.

Hardware security provided a particularly fertile research area because users often assume that a dedicated chip is intrinsically safer than ordinary software. Smart cards and trusted hardware modules can isolate private keys and make unauthorised extraction more difficult. Yet their protection depends upon manufacturing choices, firmware, random-number generators and the resistance of physical interfaces to observation or manipulation. The practical testing of such components calls for a combination of mathematical cryptanalysis, electrical engineering and controlled experimentation. Czech researchers examined how apparently harmless variations in public information or implementation behaviour might disclose properties of secret operations. This focus represented more than the search for one defective commercial device, since general methods could reveal problems shared by whole families of implementations. Collaboration between university specialists and international security communities was essential because affected hardware was often manufactured and deployed outside Czechia. The resulting work demonstrated how a relatively compact academic team could produce findings with global practical consequences. It also illustrated the need to separate the discovery of a weakness from the later engineering and regulatory measures used to mitigate it.

A major step towards systematic evidence was reported by Petr Švenda and colleagues in their 2016 paper The Million-Key Question. The Masaryk University team studied more than sixty million freshly generated RSA key pairs produced by software libraries and smart cards (Švenda et al., 2016). Their analysis demonstrated that features of public keys could reveal statistical traces of the algorithms and devices that had generated them. Such fingerprints allowed researchers to classify likely key origins even when implementation details were not otherwise available. The work challenged a common intuition that a correctly formatted public key could not disclose information about the hidden procedures used to create it. Classification of key origins did not automatically mean that private keys could be reconstructed, and the paper made the distinction important to its security implications. Nonetheless, the same technique could assist investigators in locating families of keys associated with particular implementation weaknesses. It also raised privacy questions because identifying the source of a key could narrow the anonymity of users relying upon cryptographic identities. The publication received a best-paper award at the 2016 USENIX Security Symposium, confirming substantial peer recognition of its methodology. Its significance lay in converting a cryptographic implementation concern into a measurable, large-scale empirical problem.

The 2017 discovery known as the Return of Coppersmith's Attack (ROCA) provided an even more direct illustration of the consequences of flawed key generation. Matúš Nemec, Marek Sýs, Petr Švenda, Dušan Klinec and Vashek Matyáš analysed RSA moduli generated by a widely used

Infineon cryptographic library. They found that the structure imposed during prime generation allowed a practical factorisation attack against affected keys under specified conditions. Because the weakness could be identified from a public key, operators could test deployed credentials without first recovering the private material. Vulnerable implementations appeared in products including smart cards and security tokens, demonstrating the reach of a shared underlying component. The researchers coordinated disclosure before publication, allowing manufacturers and administrators to prepare mitigations for affected systems. Their paper, The Return of Coppersmith's Attack: Practical Factorization of Widely Used RSA Moduli, appeared at the 2017 ACM Conference on Computer and Communications Security. It also showed that responsible vulnerability disclosure is a research practice with social consequences, not merely the final step in an academic publication. ROCA remains a clear example of Czech-based research influencing an international response to a concrete engineering defect.

Side-channel research investigates information inadvertently revealed by the physical or computational behaviour of cryptographic operations. Timing, power consumption, cache access and other observable effects can correlate with secret-dependent calculations. Attackers need not invalidate the mathematical algorithm if the implementation leaks enough information to reconstruct sensitive parameters. The Minerva research reported by Jan Jančár and colleagues in 2020 investigated weaknesses arising from information about the bit lengths of nonce values used in digital signatures. Their analysis concerned the Elliptic Curve Digital Signature Algorithm (ECDSA), which requires carefully generated per-signature secret values. Even limited and noisy leakage could be combined with mathematical techniques to undermine security under appropriate conditions. This kind of work is especially important for devices that process cryptographic operations repeatedly and may expose measurements to a capable adversary. Czech researchers contributed both analytical techniques and experimental evidence about the risks of supposedly small implementation leakages. The broader implication is that trustworthy cryptography requires sound algorithms, secure implementations and defensible assumptions about observable behaviour. Results of this kind also inform the design and evaluation of future authentication technologies rather than merely documenting weaknesses in older systems.

Secure authentication and privacy-preserving protocols formed another notable field of Czech applied cryptography. Researchers in Brno, including Jan Hajný and Lukáš Malina, studied methods for verifying authorised access while limiting unnecessary disclosure of identity attributes. A conventional login often proves possession of a credential by revealing a stable identifier to the service receiving it. Privacy-enhancing designs investigate whether a person can demonstrate the required entitlement without disclosing additional details. Relevant methods include selective disclosure, cryptographic credentials and protocols for authenticating constrained devices. Such techniques demand precise threat models because protection against tracking by one party may not prevent linkage through network metadata or compromised endpoints. The Advanced Cybersecurity Laboratory at Brno University of Technology developed work across authentication, applied cryptography and specialised hardware implementations. Its research illustrates the intersection between mathematical security claims and the resource limits of practical devices. Accordingly, national competence should be assessed by the quality

of demonstrable protocols and evaluations, not simply by the adoption of an internationally fashionable vocabulary.

The emergence of networked sensors and industrial computing created fresh authentication challenges that differed from those of conventional desktop systems. Embedded devices may have limited memory, restricted energy supplies and long operational lifetimes without regular physical maintenance. Conventional cryptographic procedures can impose costs that become significant when hundreds of devices must communicate frequently. Researchers therefore investigate how to preserve authenticated exchange and confidentiality while reducing computational and communication overheads. Hardware acceleration and carefully designed lightweight protocols can help, although simplifying a design may also introduce new vulnerabilities. Work associated with Brno University of Technology has addressed embedded security, privacy protection and implementations on programmable or resource-constrained platforms. Such research is relevant to smart infrastructure and industrial communications, but the mere deployment of connected equipment does not constitute a Czech cryptographic innovation. Reliable evaluation requires comparisons of security properties, hardware resources and the actual operating environment. The importance of this direction increased as ordinary industrial components became connected to enterprise networks and remote maintenance services. It demonstrates why cybersecurity research must accommodate diverse technical constraints without weakening the clarity of its security assumptions.

Developments in quantum computing prompted a further reassessment of long-term cryptographic protection during the final years of the study period. Certain mature public-key systems depend on mathematical problems that sufficiently capable quantum computers could eventually solve much faster than conventional machines. This prospect encourages research into alternative algorithms and secure transitions, although the existence of a small experimental quantum processor does not imply that existing cryptography has already become unusable. Post-quantum cryptography aims to develop methods whose security is not known to collapse under established quantum algorithms. Evaluating these candidates involves the strength of mathematical assumptions, implementation costs and resistance to conventional as well as physical attacks. Brno research projects addressed network security in the post-quantum era and hardware-assisted implementations during the early 2020s. Their importance was partly preparatory, since migration requires coordination between protocols, certificates, suppliers and organisations dependent upon long-lived data. Any assessment dated 2025 must distinguish promising research and migration planning from fully completed deployment across the economy. This distinction preserves the historical accuracy required when studying rapidly changing security technologies.

Malicious software supplied the most publicly visible expression of Czech cybersecurity, but the underlying scientific questions extend beyond detecting a familiar virus signature. Early antivirus products primarily compared suspicious files with known patterns that had already been associated with harmful programmes. Attackers responded through packing, obfuscation, behavioural variation and methods intended to defeat straightforward inspection. Research consequently moved towards analysis of execution traces, suspicious behaviour, statistical classification and relationships among malware families. These methods require dependable

labelled data, experimental isolation and precautions against contaminating the environment under investigation. Their evaluation must acknowledge that malicious and benign programmes can perform superficially similar operations. Czech commercial companies developed substantial experience through repeated exposure to evolving threats observed on users' devices. However, proprietary detection improvements and publishable scientific discoveries are not identical categories of achievement. The historical significance of the sector lies partly in the opportunity for cooperation between operational threat intelligence and academic method development. Its research value becomes demonstrable when methods, assumptions and results can be documented and critically examined.

The relationship between university research and antivirus companies provides a particularly concrete example of this exchange. Brno University of Technology conducted a project from 2011 to 2013 examining the spread of malicious code using anonymised observations associated with AVG Technologies. The project sought to extract useful knowledge from operationally collected data rather than relying exclusively upon laboratory-generated malware samples. Such collaboration allowed academic researchers to confront the uneven quality and changing behaviour of real-world threats. At the same time, privacy constraints and commercial confidentiality affected which observations could be released and reproduced. Later cooperation between the Czech Technical University in Prague and Avast further illustrated the value of connecting advanced data analysis with the operational experience of a cybersecurity company. Their joint artificial-intelligence and cybersecurity laboratory began in 2019 and focused on research relevant to detecting sophisticated malicious activity. They show instead how a mature digital industry can provide questions, datasets and application settings for scientific investigation. The principal methodological challenge is to ensure that access to industrial data strengthens rather than weakens independent assessment of research claims.

Machine learning changed malware research by allowing models to identify combinations of characteristics that hand-written detection rules might overlook. A model can compare executable properties, communication patterns or sequences of operations with patterns previously associated with harmful behaviour. Its usefulness nevertheless depends upon the representativeness of the training set and the legitimacy of the labels assigned to its examples. Malicious programmes evolve, and evaluation based on random splits of closely related samples may substantially overestimate performance on genuinely new threats. Researchers must therefore consider temporal validation, family-level separation and the possibility of deliberate evasion by an adaptive attacker. Explainability is another practical concern because analysts need to know why a system has marked an important file or service as dangerous. Czech academic-industrial research increasingly addressed such challenges in the context of large and heterogeneous operational datasets. The strongest contribution of machine learning is not the automatic replacement of professional judgement but improved prioritisation and investigation of suspicious evidence. False positives can interrupt legitimate activity, whereas false negatives can leave serious compromises undetected. Trustworthy deployment requires continual testing after release, transparent incident review and mechanisms for correcting erroneous decisions.

Threat information sharing creates a separate set of scientific and organisational difficulties. A security team may observe a malicious address, an exploited vulnerability or an unusual

communication pattern without possessing enough context to interpret it confidently. Another organisation may hold complementary evidence that changes the assessment of the same incident. Standardised descriptions and responsible disclosure channels therefore improve the possibility of producing a coherent picture from incomplete observations. Yet indiscriminate sharing can expose personal information, investigative methods or sensitive commercial details. The research problem is consequently not merely to exchange more data but to establish which information is necessary, trustworthy and legally shareable. Czech network operators, university teams and national incident-response organisations gradually developed channels for such cooperation. These practices helped turn isolated incidents into experience that could inform technical standards, exercises and preventive guidance. Cybersecurity becomes more effective when evidence can move between organisations without erasing responsibility for its origin and reliability.

The creation of a nationally recognised incident-response capability represented an important element of this institutional maturation. The Czech national Computer Security Incident Response Team (CSIRT.CZ) has been operated by the CZ.NIC association since 1 January 2011. Its responsibilities include receiving incident reports, coordinating responses and maintaining contacts with relevant domestic and international organisations. Such work is distinct from the remit of an academic research laboratory, although practical case material can stimulate important research questions. National incident-response coordination is also different from commanding every network operator, because many incidents require voluntary or contractually organised cooperation. The value of the team depends upon its credibility as a point of contact and its ability to interpret technical evidence consistently. By building relations among providers, authorities, researchers and foreign response teams, CSIRT.CZ strengthened channels through which security knowledge could circulate. Its development demonstrates how professional institutions complement scientific expertise by enabling timely action on research-relevant findings. This form of capacity is sometimes less visible than a prominent cryptographic publication but remains essential to a functioning digital environment. It should nevertheless be assessed in terms of documented services and institutional authority rather than imagined powers over all connected systems.

Security of the domain-name infrastructure became another area in which Czech organisations combined engineering development and protective research. The Domain Name System (DNS) translates human-readable names into information needed to locate Internet services. Traditional DNS mechanisms do not automatically provide cryptographic evidence that every response received by a user is authentic. Domain Name System Security Extensions (DNSSEC) add signatures and chains of trust intended to protect the integrity and origin of relevant records. CZ.NIC supported deployment of DNSSEC in the Czech top-level domain and developed open-source software related to the reliable operation of domain infrastructure. The Knot DNS server family and associated resolver technologies provide examples of engineering work whose security properties matter for networks beyond the country. Their significance should be judged through code quality, standards compatibility, independent testing and practical adoption. DNSSEC does not encrypt all queries or guarantee that a website reached through a valid domain

name is harmless. Its benefits and limitations thus illustrate the importance of matching every security claim to the specific threat against which a technology was designed.

The Turris initiative further connected national network engineering with the experimental measurement of hostile Internet activity. CZ.NIC developed security-oriented routers that could obtain updates and, with appropriate participation, contribute observations about attempts to reach exposed services. Aggregated evidence from distributed installations offered a perspective unavailable to a laboratory observing only its own network. The later Sentinel initiative sought to organise this collection and enable protective responses based on detected activity. Such systems bring researchers closer to the behaviour of attacks in ordinary domestic and small-organisational networks. They also raise difficult questions about informed participation, the minimisation of collected data and the risk of interpreting harmless scanning as a serious intrusion. A distributed sensor cannot simply reveal the intentions of every source contacting it, and classification must remain probabilistic where evidence is incomplete. The scientific value of the approach lies in reproducible measurements and inferences that can be tested against alternative explanations. Operational deployment simultaneously creates incentives to harden the software and update mechanisms of the devices serving as measurement points. Czech experimentation with secure routers therefore illustrates the productive but complicated relationship between research instrumentation and a commercially useful product.

The growth of essential digital services made cybersecurity a matter of national public policy as well as technical research. The Czech Cyber Security Act entered into force on 1 January 2015 together with its implementing regulations. The legislation established a framework for responsibilities and security measures applying to specified information systems and operators. This regulatory development did not create the mathematical principles of cryptography or the techniques of incident detection. Instead, it changed the context in which organisations were expected to manage risks, report relevant incidents and document protective arrangements. Its functions include national cybersecurity governance and responsibilities relating to protected information and cryptographic security. The emerging policy framework created demand for technical expertise capable of interpreting threats in legally and organisationally meaningful terms. University research could assist by supplying independent analyses, while operational authorities carried distinct statutory responsibilities. The separation between scientific evidence and public decision-making remains crucial when evaluating the development of national cybersecurity competence.

European integration reinforced these changes by introducing common regulatory expectations for networks, information systems and personal data. The European Union's General Data Protection Regulation (GDPR) became applicable on 25 May 2018 and profoundly affected the treatment of information about identifiable individuals. Its requirements concern lawful processing, transparency, minimisation and accountability rather than simply prescribing the use of a particular encryption algorithm. Security mechanisms can support compliance, but a technically encrypted dataset may still have been collected or used without a valid legal basis. This distinction matters for research institutions whose studies often rely upon logs containing network addresses, behaviour patterns or authentication records. Pseudonymisation can reduce some disclosure risks while still leaving information within the scope of personal-data protection

when re-identification remains possible. Researchers must therefore consider collection purposes, retention, access controls and publication practices when designing empirical cybersecurity studies. The discipline's methodological integrity depends partly upon whether its datasets were gathered and analysed responsibly. Czech organisations had to adapt these practices within a common European framework while maintaining their national technical and institutional capacities. The resulting environment brought privacy engineering into closer conversation with law, system design and the ethics of scientific evidence.

Digital identity provides a concrete setting in which these different requirements converge. A useful authentication system must establish that a claimant is entitled to perform a particular action without making every service depend upon unlimited access to personal information. Electronic identities involve registration, credential issuance, verification, recovery and revocation rather than merely a successful password check. Trust can be undermined at any of these stages if enrolment is fraudulent or recovery procedures are weak. Czech public digital services developed identity mechanisms that increasingly interacted with European requirements for electronic identification and trust services. The national identification architecture and subsequent electronic-document initiatives made the usability of secure authentication a matter of everyday public administration. Secure deployment also requires the ability to audit providers and respond when a credential or authentication device is lost or compromised. Privacy-preserving research raises further questions about whether an individual can prove eligibility without disclosing unnecessary attributes. The Czech experience therefore offers a practical environment in which abstract questions about trust intersect with institutional responsibilities and citizens' expectations.

Trusted information systems require protections that operate throughout the software lifecycle rather than only at the moment a user logs in. Software may be compromised through unsafe dependencies, insecure configuration, untested updates or errors in the handling of external input. Formal verification attempts to express selected system properties precisely and demonstrate that they hold under specified assumptions. Testing remains indispensable, but successful tests cannot prove the absence of all possible faults in a complex programme. Security engineering therefore combines code review, access controls, careful deployment procedures, monitoring and well-defined recovery arrangements. The trustworthiness of a component must also be evaluated in relation to the environment in which it operates. A cryptographic library can be mathematically sound yet become unsafe when integrated incorrectly into an application. Czech university and industrial research encountered these problems through security-critical software, authentication systems and the maintenance of networked infrastructures. The most meaningful research contributions formulate verifiable methods or produce evidence that changes how such systems can be designed and assessed. Trust should thus be understood as a justified and continuously revisited claim rather than a permanent label attached to a finished product.

Supply-chain security added another dimension because modern services depend upon code and hardware acquired from many separate producers. An organisation may apply appropriate internal controls while remaining exposed through a compromised update channel or a defect in an external component. Open-source software can facilitate independent inspection, but public

availability of code does not guarantee that every weakness has been discovered or corrected. Conversely, closed-source products may have strong security processes without providing outsiders with complete evidence about their implementation. Research must therefore evaluate provenance, update practices, component dependencies and the assumptions underlying claims of certification. ROCA demonstrated how a single flawed library could affect numerous products sold under different names and deployed by unrelated organisations. The lesson extends to cloud services, authentication platforms and industrial systems whose dependencies may be difficult for users to observe. National resilience consequently depends in part upon the capacity to investigate shared weaknesses and coordinate responses across suppliers and operators. It cannot be achieved simply by choosing domestic rather than foreign software or by treating one procurement standard as a substitute for technical scrutiny.

Practical cybersecurity competence also depends upon the ability to rehearse decisions under conditions resembling a real incident. Masaryk University developed the KYPO cyber range from 2013 as an environment for controlled simulation of complex networks and attacks. Researchers designed virtual infrastructures that participants could defend without endangering operational services. The platform supported technical exercises, learning activities and the investigation of responses under time pressure. A 2017 publication by Jan Vykopal and colleagues described its design and use cases, including the advantages of cloud-based deployment. KYPO was released as open-source software in 2020, extending its potential value beyond the original institution. Its significance was not the invention of cybersecurity training, which had an established international history. Rather, the Czech contribution lay in a documented and reusable architecture for constructing and evaluating realistic exercises. The research also examined the interaction between technical responses, teamwork and the decisions made by participants. Such work connects the human dimensions of security to experimental design and provides a complement to purely cryptographic or algorithmic research.

A realistic exercise is scientifically valuable only when its intended learning outcomes can be assessed independently of the excitement it generates. Participants may detect a simulated intrusion yet fail to preserve evidence, communicate uncertainty or coordinate remedial actions. Conversely, an exercise that rewards rapid decisions without appropriate verification may teach habits that would be damaging in an actual incident. Research on cyber ranges therefore investigates reproducibility, scenario difficulty, participant feedback and meaningful measures of performance. It must also distinguish between skill acquisition and prior familiarity with a particular training platform. In the Czech context, work associated with Masaryk University and national cybersecurity exercises created opportunities to examine these educational problems empirically. Shared scenarios can support comparison across cohorts, but the wider range of genuine attacks is difficult to reproduce in a closed simulation. The credibility of a training programme depends upon how well it acknowledges that limitation and updates its assumptions. In this way, cybersecurity education itself became a legitimate object of research rather than a peripheral service offered by established laboratories.

Cloud computing and scientific infrastructures brought the question of trust into increasingly distributed organisational settings. University researchers and industrial teams began relying upon shared computation, remote storage and services administered beyond the immediate

control of their users. Such arrangements can improve resilience through professional management and replication, but they also create dependencies on identity services, network connectivity and external providers. The confidentiality of stored research information depends on access policies, key management and the handling of privileged administrative roles. Integrity requires records of changes and procedures that can reveal unauthorised modifications, while availability depends on planning for failures and recovery. Czech research infrastructures, including the services associated with CESNET and cooperating scientific institutions, confronted these requirements as digital research expanded. The relevant security questions are not unique to Czechia, but their practical investigation contributes to national technical competence. Researchers must also distinguish between a cloud provider's contractual assurances and independently demonstrable protective properties. Increasing reliance on shared infrastructure therefore made auditability and transparent responsibility central elements of trustworthy computing. This development linked cybersecurity with the broader organisation of contemporary scientific work rather than confining it to specialised defensive departments.

Critical infrastructures and industrial control environments introduced further complications because protective measures may affect the safety and continuity of physical processes. An interruption to a hospital information system, energy-management platform or transport service can have consequences unlike those of a compromised personal computer. Some industrial devices cannot be updated frequently, and their software may depend on specialised interfaces that are difficult to replace. Security researchers consequently examine segmentation, monitoring, authentication and recovery under operational constraints. Decisions about protection must take account of engineering safety, availability requirements and the realistic capabilities of staff maintaining the systems. Czech universities and technical research groups addressed related issues through secure communications, embedded technologies and interdisciplinary projects. Testing should therefore recognise possible interactions between security controls and the industrial processes being protected. The challenge is to provide justified confidence without assuming that systems connected to the physical world behave like ordinary office networks. This field illustrates the increasing convergence of digital security, engineering reliability and public welfare.

Czech cybersecurity research developed within an international scientific environment that shaped the meaning of its national achievements. Mathematical attacks, security protocols and software tools are evaluated by communities whose members work across countries and institutions. International publication and responsible disclosure can therefore be more informative than a claim that a particular technique belongs exclusively to one national tradition. The ROCA and million-key studies demonstrate that research carried out at a Czech university can illuminate security weaknesses in products used globally. The KYPO work and national networking projects show a different kind of contribution through reusable infrastructures and accumulated operational methods. Industrial cooperation offers access to scale and realistic threats, but also requires care when interpreting commercially sensitive evidence. Public authorities contribute regulatory and coordination capabilities that should not be confused with authorship of scientific discoveries. The analytical value of separating these categories is that their successes and limitations can be assessed using criteria appropriate to each. By 2025,

Czech competence rested on the interaction of rigorous research, specialised institutions, technical entrepreneurship and international cooperation. None of these elements alone provides a complete account of the country's progress in trustworthy information systems.

The historical trajectory from 1993 to 2025 consequently reveals a broadening conception of what it means for a computer system to be trustworthy. Early concerns about access and network administration expanded into experimental cryptanalysis, malware intelligence, secure communication, privacy engineering and the governance of essential services. Research at Masaryk University supplied internationally recognised examples of how seemingly secure hardware can reveal exploitable weaknesses. Networking institutions developed practices for observing attacks, coordinating responses and improving the integrity of Internet infrastructure. National authorities established frameworks for accountability, while European requirements made the handling of personal information a central technical and organisational concern. The scientific challenge remained the ability to formulate testable hypotheses, report limitations and reproduce results wherever ethical and legal conditions permitted. Security was never a finished achievement because systems, attackers and patterns of social dependence continued to change. The Czech experience demonstrates that durable protection depends on research cultures willing to test established assumptions and translate evidence into better engineering. Within the broader history of Czech computer science, cybersecurity thus represents the continuing negotiation between mathematical confidence, empirical uncertainty and public trust.

High-Performance Computing, Parallel Algorithms and Computational Modelling

High-performance computing (HPC) became one of the clearest expressions of the transformation of Czech computer science between 1993 and 2025. Its history concerns not merely the acquisition of faster machines but the intellectual methods that make difficult computations mathematically credible and practically achievable. Scientists employ parallel systems when a problem exceeds the available processing time, memory capacity, or data-handling capabilities of an ordinary computer. Such problems include simulations of physical phenomena, analyses of molecular interactions, reconstructions of biomedical images, and training of exceptionally demanding learning models. The effectiveness of these activities depends upon numerical theory, algorithm design, software engineering, and the organisation of shared computational resources. A powerful processor cannot compensate for an unstable approximation, a poorly partitioned problem, or an erroneous scientific interpretation. Czech research consequently evolved through an interaction between methodological expertise inherited from earlier decades and new national and European infrastructure. The development was particularly visible in Ostrava and Brno, although Prague and other universities maintained important complementary traditions. By 2025 the country's computing landscape included

national supercomputers, distributed academic resources, scientific cloud services, and access to European facilities. The central question is how these capabilities enabled Czech researchers to develop original methods and participate meaningfully in computational science rather than simply purchase equipment.

The Czech Republic inherited substantial foundations for numerical computation from Czechoslovak mathematics, engineering, physics, and technical informatics. Before independence, researchers already investigated differential equations, numerical approximation, optimisation, system simulation, and the organisation of computational tasks. These disciplines were cultivated in universities, Academy institutes, industrial laboratories, and specialised computing workplaces. However, access to modern hardware was affected by procurement constraints, uneven technological development, and the organisational priorities of a centrally planned economy. The political opening after 1989 improved opportunities to obtain international literature, software, equipment, and collaborative experience. Independence in 1993 changed the institutional responsibility for sustaining research but did not remove accumulated mathematical or engineering knowledge. Throughout the 1990s, small multiprocessor machines, workstation clusters, and networked laboratories provided alternatives to reliance on isolated central systems. Parallel scientific computation therefore emerged through incremental modernisation and the creative adaptation of existing expertise. This distinction between technological inheritance and institutional reorganisation is necessary for understanding later investment in national supercomputing.

Early post-1993 computational research was geographically distributed and frequently depended upon collaboration between individual universities and research groups. Researchers seeking to solve larger problems had to assemble local computing resources and negotiate access to facilities beyond their immediate departments. The growing academic internet made it possible to connect laboratories and share computational work across institutional boundaries. Networking alone did not create a functioning distributed computer, because users also needed compatible software environments, authentication, scheduling, and technical assistance. The process encouraged Czech specialists to acquire expertise in systems administration, parallel programming, and resource coordination. It also widened awareness that a national research system would benefit from combining machines already available at different universities. In this setting, computational infrastructure was gradually recognised as a common scientific service rather than the exclusive property of a single laboratory. Such arrangements supported disciplines with intermittent but exceptionally intensive workloads, including experimental data processing and numerical simulation. They also prepared researchers for the internationally developing concepts of grid computing and shared electronic research infrastructures. The eventual establishment of national centres should therefore be viewed as a further stage of integration rather than the original introduction of scientific computation.

MetaCentrum offers a revealing example of how Czech institutions responded to dispersed computing resources before the era of major national supercomputers. Its history traces its establishment to 1996, following earlier initiatives to create high-performance computing facilities at several universities. The project's organising principle was to combine geographically separated capacity instead of requiring every scientific group to maintain its own isolated

computing environment. From 1999, MetaCentrum became one of the strategic projects associated with the Czech Education and Scientific Network (CESNET), the national academic networking organisation. Its development reflected a practical understanding that computational power becomes more valuable when accompanied by shared knowledge, stable procedures, and user support. Individual clusters differed in processor architecture, memory availability, software installation, and institutional governance. This heterogeneity required mechanisms for distributing jobs while respecting resource limitations and local responsibilities. The resulting experience supplied a national foundation for later grid and cloud research services. MetaCentrum demonstrates that the history of Czech supercomputing includes organisational innovation as well as successive generations of hardware.

Parallel algorithms constitute the scientific bridge between increasingly capable machines and the problems that researchers seek to investigate. A sequential procedure carries out operations in an ordered progression, whereas a parallel procedure organises independent or partially independent calculations for concurrent execution. The simplest division of work is often inadequate because tasks interact and exchange intermediate information. Researchers must therefore examine dependencies, communication costs, memory access, and the uneven distribution of computational effort. A procedure may perform impressively on a small cluster yet deteriorate when expanded across thousands of processors. The resulting difference between theoretical and observed acceleration makes performance measurement a central element of research. Czech groups worked with message-passing systems, shared-memory parallelism, specialised accelerators, and later heterogeneous architectures that combine several hardware types. The Message Passing Interface (MPI) facilitated communication between distributed processes, while shared-memory methods provided different opportunities within computational nodes. Scientific value arose from devising algorithms that remained accurate, efficient, and reproducible across realistic workloads. The increasing importance of these questions connected parallel computing with numerical analysis, software architecture, and the study of complex physical systems.

Computational modelling begins with the mathematical representation of a phenomenon rather than the installation of software on a cluster. In engineering and natural science, differential equations frequently describe transport, diffusion, elasticity, fluid motion, and other processes evolving through space and time. Analytical solutions are often unavailable for realistic geometries, material properties, and interacting boundary conditions. Numerical researchers consequently approximate a continuous problem with a finite collection of quantities that computers can manipulate. Finite element and finite volume methods are among the approaches used for constructing such approximations in scientific and engineering practice. The resulting systems may contain millions or billions of unknowns and require specialised sparse numerical methods. Increasing resolution can improve the representation of a physical process but also intensifies demands on memory, calculation, and communication. A credible simulation must therefore balance convergence, stability, physical assumptions, and computational cost. The Czech contribution is best assessed through identifiable improvements in methods and reliable implementations rather than through the largest model size alone.

Domain decomposition became particularly important within Czech research because it offers a route from complex numerical problems to parallel computation. The underlying idea is to divide a computational domain into smaller regions whose local equations can be solved with substantial independence. These separate calculations must remain mutually consistent at their interfaces, which creates an additional mathematical problem. Different algorithms impose this consistency through carefully designed constraints, interface variables, and iterative correction procedures. The Finite Element Tearing and Interconnecting (FETI) family provides influential methods for dividing finite element models while coordinating solutions across subdomains. Their usefulness depends on mathematical conditioning, the structure of interfaces, the properties of materials, and the distribution of work between processors. Czech research groups investigated adaptations of such methods for large problems in mechanics and related disciplines. This research should not be represented as the national invention of domain decomposition, whose foundations and development are international. Its distinctive significance lies in advanced formulations, parallel implementations, and the testing of methods at demanding computational scales. The field illustrates how national research can make substantial contributions to an internationally shared body of numerical knowledge.

The ESPRESO software developed at IT4Innovations demonstrates a specifically Czech contribution to massively parallel scientific simulation. Its modules address input preparation, processing of computational meshes, construction of numerical models, solution of physical problems, and preparation of outputs. The software incorporates domain-decomposition approaches and a specialised parallel linear solver based on the FETI family. The research centre describes its methods as capable of addressing problems with exceptionally large numbers of unknowns. Such claims require attention to the underlying benchmark, hardware configuration, and distinction between demonstrated and anticipated capability. An exceptionally large computation is meaningful only when its solution satisfies scientific accuracy requirements and provides useful knowledge about the modelled process. The modular design also permits researchers to separate input handling from numerical solution and final scientific interpretation. This is important because preparing a complex mesh or distributing it between processes can itself become a computational bottleneck. ESPRESO thus represents software engineering and algorithmic research developed together rather than a general-purpose application of foreign supercomputing hardware.

A related direction has been pursued through the PERMON libraries and their applications to large-scale computational optimisation. These libraries include tools for quadratic programming and domain-decomposition methods that are particularly relevant to contact mechanics. Contact introduces challenging mathematical conditions because two bodies may touch, separate, or slide as their configuration changes. The resulting constraints make many otherwise familiar equations substantially more difficult to solve at scale. Research documented in an IT4Innovations computing-allocation project describes implementations serving mechanics, ice-sheet modelling, and other numerical applications. The same project reports calculations involving more than one billion unknowns on tens of thousands of processor cores. These results should be interpreted as evidence for specified computational experiments rather than proof of unlimited scalability. They also illustrate the scientific importance of reusable solver libraries that

researchers can incorporate into distinct disciplinary models. Czech expertise in numerical optimisation thereby links abstract mathematical analysis with computationally demanding questions in engineering and environmental science. The ability to maintain and extend such software is itself a substantial research capability.

Preconditioning is another essential subject because even correctly formulated linear systems may resist efficient numerical solution. Iterative algorithms often approach an answer through successive improvements rather than computing a direct factorisation of the entire system. Their convergence rate depends strongly upon mathematical properties that can deteriorate when models become larger or more heterogeneous. A preconditioner changes the computational representation in ways intended to make convergence faster without altering the underlying scientific solution. Constructing an effective preconditioner requires understanding both the mathematical operator and the parallel machine on which calculations are performed. The balance is delicate because a powerful preconditioner may itself demand excessive communication or memory. Czech developments in finite element solvers and optimisation libraries contributed to practical strategies for managing this balance. Researchers also had to assess numerical precision and the consequences of rounding error when very large systems were distributed across processors. The resulting work demonstrates why useful high-performance computing research cannot be measured by processor speed or hardware utilisation alone.

The appearance of graphics processing units (GPUs) created opportunities and new difficulties for computational researchers during the 2010s. Originally associated with graphics operations, these accelerators became widely used for numerical kernels involving large quantities of relatively regular calculations. Their performance is influenced by memory coalescing, the distribution of threads, occupancy, and the movement of data between system components. Algorithms developed for central processing units cannot always be transferred unchanged while preserving efficiency. Furthermore, a machine may contain several accelerator types whose optimal implementation parameters differ substantially. Czech research increasingly investigated how application kernels could exploit these architectures without sacrificing numerical reliability or portability. This required collaboration between programmers familiar with hardware behaviour and scientists who understood the mathematical meaning of each calculation. The challenge was to optimise complete scientific workflows rather than isolated fragments that looked impressive in artificial benchmarks. The move towards heterogeneous computing consequently encouraged deeper investigation of software adaptability and automatic performance tuning. It also anticipated the intensive use of accelerators for machine learning and scientific data analysis in the following decade.

A concrete example arose from the High-Performance Computing Research Group associated with Masaryk University's CERIT Scientific Cloud in Brno. Researchers including Jiří Filipovič developed methods and tools intended to improve the performance of computational kernels across different accelerator architectures. One important output was the Kernel Tuning Toolkit (KTT), which explores alternative configurations of programs to identify efficient implementations. The method can adjust parameters during application execution instead of relying exclusively on a single configuration selected in advance. This is valuable because the

fastest implementation may change with the size and structure of the input data or with the available device. The group's work connected algorithmic optimisation with low-level performance measurement and the practical requirements of scientific software. It also reflected a distinctive institutional approach in which specialists in computation collaborated closely with researchers in chemistry and biology. The publication record identifies dynamic autotuning as a major theme rather than presenting performance gains as an automatic consequence of newer processors. Such work contributed original methods for making scientific computation adaptable and efficient.

A 2020 article by Filip Petrovič and colleagues provides especially clear evidence of the methodological substance behind this programme. Published in Future Generation Computer Systems, it examined highly efficient kernels written with different accelerator programming approaches. The authors assembled a benchmark set and investigated systematic searches for configurations that improved performance on available hardware. They also demonstrated how performance parameters could be reconsidered dynamically as applications continued to operate. The significance lies in a general method of performance optimisation rather than a speed record on one individual machine. A reproducible benchmark allows other researchers to scrutinise claims and assess whether improvements apply beyond the original experimental configuration. Dynamic tuning also creates overhead, so the potential gains must be weighed against the time spent searching for better parameter choices. This trade-off is particularly important when a short computation cannot recover the cost of optimisation. The study illustrates a mature research question at the intersection of algorithms, computer architecture, and the economics of scientific calculation. It also shows how Czech-based researchers worked within international co-authorship networks without losing the identifiability of their own contributions.

One revealing application of parallel computing concerned the movement of small molecules through the internal cavities of proteins. Such transport processes matter because access to active sites can influence enzymatic reactions, drug action, and biochemical regulation. Conventional molecular dynamics offers detailed physical information but may require extensive calculation to investigate possible pathways. A team involving Jiří Filipovič, Luděk Matyska, Jiří Damborský, and collaborators developed CaverDock to examine ligand transport more efficiently. Their approach combined molecular docking with a procedure for constructing plausible contiguous movement through protein tunnels. The reported implementation used a parallel heuristic search to obtain trajectories and energetic profiles at lower computational cost than a full molecular dynamics simulation. This difference does not make one method a universal replacement for the other because they answer related but distinct scientific questions. Rather, it illustrates how algorithmic simplification and parallel implementation can extend access to otherwise demanding investigations. The research joined Masaryk University's computational expertise with laboratory knowledge relevant to protein engineering and biotechnology.

Scientific image reconstruction provides another example in which computational methods contributed directly to the quality and speed of biological research. Cryo-electron microscopy produces observations from which researchers infer three-dimensional structures of molecules and larger assemblies. The reconstruction process involves intensive transformations and

aggregation of large amounts of image data. David Střelák, Jiří Filipovič, and international collaborators published an accelerator-oriented approach to three-dimensional Fourier reconstruction in 2019. Their implementation reconsidered memory-access patterns to improve locality and reduce conflicts during parallel writing. It was integrated into the established Xmipp software environment used for cryo-electron microscopy analysis. The authors reported substantial performance improvements for specified comparisons, including an acceleration relative to a parallel central-processor implementation. The general importance of the study lies in the interaction between algorithm design, memory organisation, and the requirements of a real scientific workflow. It demonstrates that computing research can change the practicality of experimental analysis without itself constituting a new biological discovery. The international character of the publication also exemplifies how Czech computational groups contributed specialised expertise to broader research collaborations.

Computational chemistry and materials science became significant beneficiaries of Czech high-performance resources during the period under review. Calculations of electronic structure, molecular interaction, reaction pathways, and material properties often involve mathematical approximations too expensive for ordinary workstations. Researchers therefore combine specialised simulation software with parallel processors and carefully selected numerical parameters. The scientific result depends upon the theoretical model and basis of approximation, not merely the number of completed computational jobs. National supercomputer services have supported investigations in these areas, as illustrated by IT4Innovations records of work conducted on the Anselm system. According to the centre, Anselm processed projects in materials science, computational chemistry, biosciences, and engineering during its operation. Such applications provide evidence of access and use but do not automatically establish that every scientific discovery originated within the supercomputing centre itself. The contribution of infrastructure is frequently to make a researcher’s chosen method feasible at higher resolution or across more candidate systems. Materials modelling also illustrates how greater computational capacity can support experimental planning and the interpretation of measurements obtained in laboratories.

Engineering simulation poses a related but distinct set of computational problems because realistic machines and structures rarely exhibit the simplicity of textbook models. Mechanical components may experience deformation, temperature variation, fluid loading, and frictional contact under changing operating conditions. Computational fluid dynamics (CFD) provides methods for investigating flows that are costly, dangerous, or otherwise difficult to reproduce experimentally. The algorithms must represent conservation laws and boundary conditions while managing turbulence, complex geometries, and numerical instability. Parallel computation can divide large spatial meshes among processing units, although the resulting interfaces require repeated exchange of information. Researchers also need tools for checking whether numerical predictions remain credible when mesh resolution or timestep is changed. Czech teams associated with technical universities have developed modelling and solver expertise for industrially relevant problems, including difficult coupled mechanical calculations. Projects of this kind demonstrate the potential value of linking applied mathematics, engineering specialists, and high-performance computing services. However, simulation outputs should be understood

as conditional predictions that require experimental or independent numerical validation. The practical achievement is therefore improved capacity for disciplined design and analysis rather than the replacement of engineering judgement by computation.

Energy and environmental problems broadened the scope of computational modelling beyond individual industrial components. Thermal transport, atmospheric processes, pollution dispersion, and large mechanical systems can involve interacting physical mechanisms operating at several spatial scales. A detailed representation may require researchers to combine equations that describe different phenomena and exchange information between their solutions. This is known as multiphysics modelling and can create computational demands larger than those of the component problems considered separately. For example, a model coupling flow and heat transfer must coordinate velocity, pressure, and temperature while preserving the assumptions of each numerical method. Parallel algorithms can help reduce time to solution, but the complexity of data movement and iterative coupling increases. Scientific teams therefore rely on both disciplinary expertise and specialists who understand the behaviour of large computational architectures. The national infrastructure provides opportunities to investigate scenarios that would be impractical on smaller systems. The interpretation of outputs nevertheless requires uncertainty assessment, sensitivity analysis, and awareness of limitations in available observations.

Biomedical modelling illustrates particularly clearly why access to computing resources must be accompanied by careful data governance and methodological discipline. Numerical research may investigate tissue mechanics, molecular interactions, medical images, or biological systems whose behaviour changes across many scales. More detailed models can assist hypothesis formation and the design of experiments, but their apparent precision may exceed the reliability of available measurements. Patient-related information introduces additional requirements concerning confidentiality, secure access, and the reproducibility of analyses. A researcher using a shared computation service must therefore distinguish public model parameters from sensitive input records and controlled results. Flexible cloud environments can be more appropriate than a conventional batch queue when analyses require bespoke software, services, or protected data workflows. At the same time, not every biomedical task benefits from a larger supercomputer, especially when the model or dataset is relatively small. Scientific value lies in selecting the computational environment that serves the research question while respecting legal and ethical constraints. This approach links developments in high-performance computing to the broader responsibilities of trustworthy computational research. It also prevents technological capacity from being confused with clinical validation or medical effectiveness.

Weather, climate, and environmental simulation provide a further illustration of the limits and opportunities of computational power. Atmospheric models divide a continuous physical system into numerical cells and repeatedly evaluate changes in quantities such as temperature, pressure, moisture, and wind. Increasing spatial resolution may allow more detailed representation of local processes while sharply increasing the number of operations required. Long simulations and ensembles of alternative initial conditions create additional demands on processing time and storage. Parallel architecture is therefore central to the operation of major environmental modelling systems worldwide. Within Czechia, university researchers and

specialised scientific organisations have participated in computational approaches relevant to environmental analysis and physical modelling. The existence of domestic supercomputing capacity widens the range of methods that such research communities can realistically investigate. Nevertheless, general international developments in climate modelling should not be represented as specifically Czech discoveries without evidence of identifiable scientific contributions. The national achievement is better assessed through documented research, implemented methods, and access to appropriate resources.

A decisive institutional stage began with the development of IT4Innovations at VSB (Vysoká škola báňská)—Technical University of Ostrava in the early 2010s. The centre's project was launched in 2011, creating a framework for combining large-scale computing services with dedicated scientific research. Its first supercomputer, Anselm, entered service in 2013 and provided a theoretical peak performance of approximately ninety-four trillion floating-point operations per second. The system used interconnected processing nodes and included specialised accelerator equipment for workloads suited to that architecture. Anselm's significance lay in national access to an organised resource with common user procedures, professional support, and specialised technical facilities. The official operating record reports more than 2.6 million jobs across 725 research projects before its retirement in January 2021. These numbers indicate sustained scientific use but do not by themselves establish the quality of all resulting publications. The opening of the Ostrava centre also gave local research groups opportunities to investigate scalable software within the same institutional environment as demanding hardware. This combination strengthened the relationship between the provision of computing resources and the creation of original computational methods. It marked a shift from dispersed national arrangements towards a major physical centre for advanced scientific computing.

The installation of the Salomon supercomputer in 2015 substantially enlarged Czech computing capacity and strengthened the centre's international visibility. Its theoretical peak performance approached two quadrillion floating-point operations per second, placing it among prominent European systems at the time. The subsequent operation of Barbora, installed in 2019, added another major resource within the national infrastructure. That year also brought a specialised system designed for workloads involving artificial intelligence and accelerators rather than conventional central processors alone. Together, these investments supplied alternative architectures with different performance characteristics and operational purposes. Researchers therefore needed to choose hardware according to memory demands, available accelerators, communication requirements, and software support. Anselm and Salomon were retired in 2021, showing that major scientific computers have limited operational lifetimes despite their considerable acquisition costs. The centre's institutional importance consequently depended not simply on accumulation of machines but on replacing equipment while maintaining research support and technical expertise. This cycle of renewal became a central challenge for the sustainability of Czech scientific infrastructure.

Karolina, commissioned at IT4Innovations in 2021 through European cooperation, represented another transformation of the Czech computational environment. The system provided a theoretical peak performance of approximately 15.7 quadrillion floating-point operations per second. Its architecture supported both conventional simulation and workloads requiring

graphics accelerators, including advanced analysis and machine learning. The machine also demonstrated how European funding and national institutional responsibility could be combined in a shared research infrastructure. Although hardware specifications provide useful context, they cannot be read as the performance achievable by every scientific programme. Application speed depends on parallel efficiency, mathematical operations, memory access, and the interaction between processors. A system capable of delivering impressive benchmark results may still perform modestly when a particular scientific model cannot be divided efficiently. The scientific meaning of Karolina is therefore found in both expanded capacity and improved opportunities for specialised software research. By the end of 2025, it formed a central component of Czech access to high-performance computing within the European research landscape. Developments initiated after that date belong to a later historical period and are not treated as completed achievements here.

The development of cloud computing created opportunities to support workloads that did not match traditional high-performance queue arrangements. MetaCentrum Cloud used the OpenStack platform to provide configurable virtual machines through a research-oriented infrastructure. Researchers could deploy specialised operating environments and manage their own applications without requesting the installation of every component by cluster administrators. This flexibility was valuable for complex analysis pipelines, experimental software, and services with persistent operational requirements. Virtual machines nevertheless introduce management obligations and may not provide the same performance characteristics as tightly integrated supercomputing nodes. The availability of several environments therefore encouraged scientific users to consider efficiency, convenience, security, and technical complexity together. At CERIT-SC, infrastructure research also focused on combining virtualisation with computational accelerators and scientific software support. Such work demonstrates why the convergence of cloud services and high-performance computing did not eliminate important architectural differences between them. The goal was a complementary system in which researchers could select resources appropriate to their methods and data.

The integration of CESNET, CERIT-SC, and IT4Innovations within the national electronic research infrastructure (e-INFRA CZ) marked a further stage in the organisation of national digital research capacity. The common infrastructure began operating in 2020 and brought networking, computation, and storage into a more explicitly coordinated framework. Its published description identifies high-speed communications, national grid and cloud facilities, supercomputers, and repositories as complementary services. For scientific users, this combination reduces the fragmentation created when separate providers maintain incompatible procedures and support arrangements. The achievement is not the disappearance of institutional differences, since each component retains its specialised tasks and technical characteristics. Rather, the network allows researchers to organise investigations requiring data transmission, storage, analysis, and access to high-performance facilities. Large contemporary projects frequently depend on all these functions and can be hindered when they are planned independently. The integrated model also encourages the establishment of consistent user support, authentication, and allocation practices. Its importance should therefore be understood as infrastructural and organisational innovation that enables, but does not replace, original scientific inquiry. The development

reflects a wider European movement towards connected research environments and reproducible digital workflows.

The management of computational workloads represents a substantial technical discipline within shared national infrastructure. Researchers rarely receive exclusive use of an entire supercomputer, so many projects must compete for processing time, memory, storage, and support. Schedulers organise tasks according to defined priorities, resource requests, system policies, and the practical availability of nodes. A poorly specified job can waste valuable capacity or fail before producing useful results, even when its mathematical method is sound. Scientific workflows consequently require realistic performance estimates, monitoring, recovery procedures, and arrangements for processing large output files. IT4Innovations makes computing capacity available through open-access competitions, an approach that connects allocation with proposals and assessment of intended research. The evaluation of requests must distinguish ambitious but feasible calculations from proposals that have not yet established a suitable numerical method. Resource management also requires attention to software licences, technical training, reproducibility, and the long-term storage of results. These considerations illustrate how supercomputing expertise extends from algorithm design to the institutional organisation of scientific work.

International integration greatly expanded the significance of Czech high-performance computing during the 2010s and early 2020s. Participation in the Partnership for Advanced Computing in Europe (PRACE) linked national specialists with wider European communities concerned with large-scale computational research. The European High Performance Computing Joint Undertaking (EuroHPC JU) later provided a framework for jointly supported supercomputing investments and access programmes. Karolina was commissioned within this European framework rather than as a wholly isolated domestic acquisition. Czech researchers also gained access to LUMI, a major European supercomputer hosted in Finland, through participation in the international consortium. LUMI was inaugurated in June 2022 and involved ten participating countries, including the Czech Republic. Such cooperation illustrates that national computational capacity is increasingly measured by access, contribution, and expertise rather than ownership of machines alone. Cross-border arrangements offer opportunities for calculations whose demands would be difficult to meet through national installations. They also introduce responsibilities concerning training, project evaluation, and the transparent attribution of international scientific results. The strongest form of integration occurs when domestic research groups both use shared facilities and contribute software or methods of value to other participants.

Artificial intelligence created additional demands on computing services while changing the nature of workloads for which parallel systems were designed. Training large neural networks can involve intensive matrix calculations, communication between accelerators, and repeated movement of sizeable datasets. These activities differ from some traditional numerical simulations in precision requirements, memory patterns, and tolerance for statistical approximation. A heterogeneous supercomputer may therefore need software environments that support both established scientific codes and machine-learning frameworks. Czech infrastructure responded by providing accelerator-based systems and opportunities for research

connecting data analytics with high-performance computation. IT4Innovations identified machine learning and large-scale data processing among its principal research directions during the period under review. However, operating a powerful accelerator cluster is not equivalent to developing an original learning algorithm or an internationally significant model. The scientific contribution must be established through methods, research publications, reproducible experiments, and identifiable applications. This distinction is essential in assessing the relationship between infrastructure development and the rapidly expanding public visibility of artificial intelligence.

Energy consumption and long-term maintenance emerged as increasingly important dimensions of responsible high-performance computing. Large computing systems require substantial electricity not only for processors but also for cooling, networking, storage, and auxiliary infrastructure. Performance expressed in floating-point operations per second therefore provides only a partial measure of operational effectiveness. An application may consume more total energy if it uses additional processors inefficiently or requires excessive communication between nodes. Researchers and centre operators accordingly have reasons to examine time to solution, energy per completed task, and the suitability of hardware for particular applications. The replacement of ageing supercomputers can improve efficiency, but equipment production, disposal, and infrastructure adaptation also create environmental costs. Sustaining national resources requires predictable financing for electricity, maintenance, personnel, and periodic modernisation after original construction grants have ended. Smaller research groups must also receive opportunities to develop the skills necessary for effective and responsible use. The long-term value of Czech computing infrastructure thus depends as much on institutional continuity and transparent resource management as on acquiring the next generation of processors. By 2025, these issues had become inseparable from discussions of national digital research capacity and technological resilience.

The development of Czech high-performance computing from 1993 to 2025 reveals a layered scientific achievement rather than a single technological breakthrough. Mathematical and engineering traditions supplied an intellectual foundation that remained valuable as available machines changed. Investment in Ostrava later transformed the scale of domestic calculation and supported internationally connected research in algorithms and computational modelling. Brno contributed original software and optimisation methods that improved the efficiency and applicability of advanced scientific computation. The integration of cloud, grid, network, and supercomputing resources created a broader service environment capable of supporting heterogeneous research demands. International collaboration enabled Czech groups to participate in scientific programmes beyond the practical reach of national machines alone. At the same time, the examples of ESPRESO, PERMON, dynamic autotuning, molecular transport analysis, and image reconstruction demonstrate the importance of identifiable intellectual contributions. A rigorous national history must distinguish research conducted by Czech teams, infrastructure operated within Czechia, and collaborative results produced across borders. The lasting lesson of the period is that scientific computing advances most effectively when mathematical insight, engineering competence, institutional cooperation, and access to reliable infrastructure develop together.

Data Science, Database Technologies, Knowledge Systems and Information Analytics

The development of data science in the Czech Republic after 1993 cannot be reduced to the adoption of larger databases or faster computers. It reflects a change in the intellectual status of information, which gradually became an object of scientific investigation, industrial engineering and public governance. Computer scientists had long studied how records could be represented, retrieved and manipulated, but the independent republic inherited institutions whose information systems were often separated by organisational boundaries. During the 1990s, commercial software and increasingly accessible networks created incentives to connect information that had previously remained within individual workplaces. Universities responded by strengthening research on database structures, efficient search and the formal meaning of stored information. As the 21st century progressed, heterogeneous documents, multimedia collections and scientific measurements complicated the assumptions of traditional systems. The resulting research agenda combined theoretical questions about representation and inference with engineering problems of storage, performance, reliability and interoperability. By 2025, Czech research groups and enterprises were contributing to an environment in which information could be collected at unprecedented scale but still required careful interpretation. This chapter examines that transformation through identifiable scientific contributions rather than treating every new application as evidence of an original national discovery.

The relational model, which represents structured information through schema-governed tables, also supplied a framework for questions about the efficiency and intelligibility of information retrieval. A database query specifies a desired result, but it does not necessarily prescribe the steps by which a system should obtain that result. Different execution plans can therefore produce equivalent answers while consuming substantially different amounts of memory, processing time and storage access. Research on indexing, query optimisation and physical database organisation addresses this gap between declarative intention and computational execution. The issue became more pressing as Czech universities and enterprises accumulated records whose volume exceeded what could be handled by elementary search procedures. An efficient index may prevent the examination of every record, although the index itself requires maintenance when underlying information changes. Likewise, combining several tables can become costly when an inappropriate join order magnifies intermediate results. Such problems demonstrate why database design is a scientific and engineering discipline rather than a collection of routine administrative operations. Czech research on complex information structures subsequently expanded these concerns to data for which conventional rows and columns were no longer sufficient. The enduring achievement of this tradition lies in establishing reproducible principles for correct answers and predictable performance under changing workloads.

Prague developed an important research environment around the Department of Software Engineering at the Faculty of Mathematics and Physics of Charles University. Jaroslav Pokorný contributed to the investigation of databases and information integration during the period in which organisations were turning to more heterogeneous digital systems. His article on

Extensible Markup Language (XML) in enterprise systems examined how an exchange format could support the integration of otherwise separate information resources. The importance of XML was not that it replaced relational databases, but that it offered a structured way to describe nested documents and exchange information between applications. An enterprise could retain a relational database internally while transmitting information in a document whose fields and hierarchy were understood by another system. This possibility immediately raised technical questions about mapping, schema compatibility, validation and querying across distinct representations. Pokorný's work placed those questions within the wider problem of enterprise information integration rather than treating document conversion as an isolated programming exercise. It also highlighted the need to distinguish the meaning of data from the particular software through which the data were transmitted. The Prague contribution was therefore methodological, helping to articulate how established database principles could remain relevant when information formats diversified.

The work of Irena Mlýnková, later publishing as Irena Holubová, extended Prague's database research into the changing organisation of XML information. Her publications with Pokorný investigated approaches for processing XML documents using object-relational and relational database technologies. A central difficulty is that hierarchical documents contain nested structures and optional elements that do not correspond neatly to fixed tabular designs. Transferring such documents into tables may preserve individual values while complicating reconstruction of their original relationships. Conversely, storing them in an entirely separate system may sacrifice transaction facilities and mature query mechanisms already available in relational platforms. The research compared mapping strategies and examined circumstances in which one architecture provided advantages over another. It also made clear that performance could not be evaluated without considering the shape of real documents and the questions users intended to ask. For a public institution exchanging administrative reports, correctness of document reconstruction may be just as important as query speed. For an archival catalogue, structural changes can present a greater difficulty than the storage of an additional million records. These distinctions exemplify the practical depth behind the development of Czech research in data organisation.

A particularly consequential extension of this work concerned the evolution of schemas over time. The structure of an information system rarely remains unchanged as institutions introduce new services, legislation or scientific measurements. A medical database might acquire a new field for a diagnostic indicator, while historical records still follow an earlier version of the model. Merely changing the current schema does not explain how existing data and saved queries should continue to function. Research by Holubová and colleagues considered schema inference, compatibility, document transformation and the propagation of structural changes through applications. Such questions are especially important when data have to remain accessible for decades rather than for the lifetime of one software installation. In the study of real-world XML collections, irregularities and variations can themselves provide evidence about how information is produced in practice. Automatically inferring a schema may reveal recurrent patterns, but it can also suppress unusual cases if the algorithm is insufficiently cautious. The research

therefore connected practical database engineering with a broader problem of reconciling formal models and imperfect evidence.

During the 2010s, database research confronted a further transformation as non-relational systems gained significance in internet services and scientific computation. Document stores, graph databases and key–value systems offered different ways of representing data whose internal structure or access patterns were poorly suited to one universal model. The term NoSQL became associated with several approaches that deliberately departed from conventional relational assumptions, although it never denoted a single coherent architecture. A graph database could represent relationships among people or organisations directly, whereas a document database could preserve a nested record without flattening every element into tables. Each approach created advantages for particular operations while introducing difficulties concerning transactions, interoperability and query expressiveness. At Charles University, the investigation of multiple data models developed into a research programme concerned with their unified management. Jiaheng Lu and Irena Holubová surveyed this emerging field in a 2019 article in ACM Computing Surveys, a journal published by the Association for Computing Machinery (ACM), classifying approaches and identifying unresolved technical questions. Their analysis treated diversity as a long-term research problem rather than assuming that one new database product would render all others obsolete. This contribution established a useful conceptual reference for evaluating systems whose data reside in several logically distinct representations. Its importance lies partly in demonstrating why flexibility without principled coordination can create a new generation of information silos.

The problem of multiple data models also stimulated research into transformations, querying and structural evolution across different database representations. A single organisation might store transactions in relational tables, customer interactions in documents and complex dependencies in a graph. Analysts may then require one coherent answer assembled from all three systems without knowing the details of each storage format. A naïve approach copies everything into one repository, but duplication can create delays, inconsistencies and substantial maintenance costs. More sophisticated approaches attempt to translate queries, identify common semantics and control the movement of data between systems. Holubová's research group investigated such possibilities through multi-model modelling, schema inference and tools for unified querying. The underlying methodological challenge is to preserve meaning when operations are translated between models with different assumptions. A missing property in a document, for instance, is not necessarily equivalent to an absent relationship in a graph or a null value in a table. Czech work in this area illustrates how theoretical questions of equivalence and transformation acquire immediate significance for enterprise and scientific information systems.

Reliable integration depends not only on database formats but also on the often-neglected information describing data itself. Metadata identify such properties as the origin of a dataset, the meaning of its fields, the applicable licence and the conditions of its collection. Without metadata, an apparently precise numerical result may be misleading because its geographical coverage, measurement procedures or time period are uncertain. Data provenance goes a step further by recording how a result was produced from underlying sources and transformations. A statistical dashboard can display a confident trend even when two input files employ

incompatible definitions of the population being counted. Provenance enables investigators to trace such discrepancies rather than merely changing the final visualisation. In scientific environments, a similar record permits later researchers to reconstruct how an experimental output was cleaned, transformed and analysed. Czech research and commercial software development increasingly encountered these questions as information systems became interconnected and analytical workflows more automated. The distinction between a well-designed database and trustworthy knowledge consequently became more visible: reliable storage is necessary, but it cannot by itself validate an interpretation. The growing emphasis on lineage and reproducibility would become particularly important as automated models began incorporating data from many sources.

Brno developed a distinctive international research profile in similarity searching through the Faculty of Informatics at Masaryk University. Pavel Zezula, Vlastislav Dohnal and Michal Batko worked with international collaborators on retrieving information that could not be identified adequately through exact database matching. Their monograph Similarity Search: The Metric Space Approach, published by Springer in 2006, offered a systematic treatment of the mathematical and engineering foundations of this problem. A conventional database request may ask for an exact identifier, but an image retrieval system must identify objects that resemble a supplied example. The challenge is not limited to pictures, because comparable questions arise with audio recordings, scientific structures, videos and other complex objects. Metric spaces provide one formal approach by representing dissimilarity through a distance measure that satisfies specified mathematical properties. This formulation permits the design of search structures that eliminate candidates without examining every possible comparison. The book considered centralised indexes, approximation and distributed approaches, thereby connecting mathematical abstraction with large-scale implementation. For Czech computer science, the work represented a documented intellectual contribution to an internationally important research field rather than a mere application of imported software.

The efficiency of similarity retrieval depends on how a search system organises candidate objects before a query arrives. A direct comparison of every item can return an exact result, but it becomes costly when collections contain millions of high-dimensional descriptions. Metric indexes organise objects using distances to selected reference points, partitions or other structures that allow portions of the collection to be excluded. Their success depends on the distribution of data and on whether the chosen distance function represents the similarity sought by users. A distance that works well for one type of image may be unsuitable for medical measurements or biological structures. The Brno research tradition investigated these mathematical and practical trade-offs rather than presuming a universal index could solve every retrieval problem. David Novák, Michal Batko and Pavel Zezula published work on scalable metric indexing and precise or approximate similarity search. Approximation can reduce processing cost, but its scientific acceptability depends on the consequences of omitting some candidates. When a physician searches for comparable diagnostic images, errors may matter differently from errors in an entertainment recommendation service. This balance between correctness, speed and contextual significance remains central to modern large-scale information retrieval.

The implementation of research algorithms in reusable systems was another important characteristic of the Brno school. Batko, Novák and Zezula described the Metric Similarity Search Implementation Framework (MESSIF) in a 2007 publication on digital libraries. A software framework of this kind gives researchers a common environment in which to test indexing methods, query strategies and distributed configurations. Without comparable implementations, performance claims may reflect unrelated differences in hardware or programming practices rather than the merits of a method. Experimental reproducibility therefore becomes part of the scientific contribution, not an afterthought attached to a theoretical article. The research group also investigated architectures for searching web-scale image collections and data distributed across multiple machines. Such designs must decide how objects are partitioned, how partial answers are combined and when communication costs outweigh local computation. The importance of these studies extended beyond one platform because similar principles arise wherever large collections must be searched under response-time constraints. They illustrate a Czech capacity to connect theoretical database research with implementable, experimentally assessed information systems.

As digital information became increasingly visual, search research expanded from simple features towards richer representations of objects and their context. The Laboratory of Data Intensive Systems and Applications (DISA) at Masaryk University studied large and complex collections including images, videos and movement data. Its work linked indexing methods with techniques for extracting descriptions that could be compared computationally. A picture of a building, for example, can be represented by colour distributions, detected structures or learned numerical features. These descriptions may capture different meanings, and a retrieval system must therefore choose how to translate a user's intention into measurable similarity. In motion analysis, the problem becomes more demanding because movements vary in speed, spatial orientation and duration. Research projects in Brno investigated searching, annotating and mining streams of recorded human movement. Their applications include identifying comparable movements in rehabilitation and analysing recordings that would be difficult to examine manually. The scientific question remains how to define meaningful correspondence without allowing superficial numerical resemblance to dominate the result. The development of these methods demonstrates how database research can produce substantive methodological advances within interdisciplinary applications.

Prague's School of multimedia retrieval developed a complementary emphasis on interactive search and the interpretation of user queries. At Charles University, Tomáš Skopal and Jakub Lokoč contributed to research on similarity search, multimedia databases and video retrieval. Their work treated retrieval as an interaction between computational representations and the knowledge of the person asking a question. A video library can contain the exact scene being sought even when the searcher cannot specify its title, date or conventional metadata. In such circumstances, the user may remember the appearance of a scene or the sequence of events rather than a searchable keyword. Interactive retrieval systems respond by combining visual descriptions, text queries, temporal navigation and successive refinements of the candidate collection. Lokoč and colleagues participated in international evaluation campaigns, including the Video Browser Showdown, where teams compare systems on defined retrieval tasks. Such

evaluations provide evidence about the practical strengths of different interfaces and indexing strategies. They do not transform competition rankings into universal scientific truths, because results remain sensitive to task design, participants and datasets.

The move from exact textual search to interactive and multimodal retrieval also altered the meaning of relevance. In a library catalogue, a record can be an exact match for a title yet fail to address the topic a researcher actually needs. In multimedia collections, exact matching is often unavailable because the same concept can appear in visually different forms. Information retrieval therefore uses ranking methods that order possible answers according to a computed assessment of their relevance. Such assessments can draw upon textual evidence, similarity measures, contextual features and feedback from users. The challenge is that relevance is partly dependent on purpose, and an algorithm cannot infer that purpose perfectly from a short query. Czech researchers in Prague and Brno investigated different dimensions of similarity, retrieval and evaluation within this broader international field. Their contributions should be understood in terms of identifiable models, search structures and experiments rather than an undifferentiated claim that Czechia created modern search engines. By 2025, retrieval research was also confronting learned vector representations, making the quality of semantic encoding as important as the organisation of stored objects. This development connected database theory increasingly closely with machine learning while preserving distinct questions about indexing, query planning and verifiable retrieval performance.

Statistical knowledge extraction provides another important branch of Czech information research, particularly where the task is to reason under uncertainty. At the Institute of Information Theory and Automation of the Czech Academy of Sciences, Milan Studený developed influential work on probabilistic conditional independence. His monograph Probabilistic Conditional Independence Structures, published in 2005, examined formal representations of relationships among random variables. Conditional independence matters because it can simplify a complicated probability distribution when certain dependencies disappear after other variables are taken into account. These principles underlie graphical statistical models and many procedures used for reasoning with incomplete information. The mathematics is subtle, since statistical association does not by itself establish a causal relationship between observed events. A decision-support application that confuses correlation with causation may therefore recommend an ineffective intervention despite producing internally consistent calculations. Studený's work belongs to a theoretical tradition whose value lies in clarifying the conditions under which structural claims about uncertainty are justified. It also shows how Czech contributions to data science extend beyond database implementations into the logical foundations of statistical inference.

Probabilistic models became more visible in practical analysis as information systems collected larger and more varied streams of observations. A model can estimate the likelihood of a machine failure, an unusual transaction or a disease outcome, but the reliability of the estimate depends upon data quality. Missing observations, selective reporting and changes in measurement practices can make a statistically sophisticated model unreliable. The task of data mining is consequently not simply to discover the largest number of apparent patterns. Researchers must distinguish patterns that generalise beyond a sample from those produced by chance or by the

assumptions of an analytical procedure. Czech work in information theory, statistics and decision-making contributed methods and concepts relevant to this distinction. In particular, graphical models help represent dependencies, while statistical validation tests whether the resulting inferences are supported by evidence. An industrial example would be identifying whether temperature readings genuinely predict equipment failure after accounting for operating load and maintenance history. The contribution of data analytics is strongest when its conclusions remain open to independent testing and revision. This principle became increasingly important as predictive systems acquired direct influence over public and commercial decisions.

The emergence of data warehouses and business intelligence created another arena in which analytical methods were translated into organisational practice. Operational databases are usually designed to support individual transactions, whereas analytical repositories often combine historical records for comparison across departments or time periods. The conversion requires more than copying tables, because the sources may classify customers, products and events differently. Data cleaning, transformation and reconciliation become crucial steps before a management dashboard can produce a defensible conclusion. In the Czech Republic, the expansion of enterprise information systems created demand for specialists who could design these analytical processes. Universities contributed through database and statistical education, while consulting firms and software developers built systems for commercial use. Such work should not be mistaken for a wholly new national theory of business intelligence, which developed internationally through many institutions. Its significance lies instead in the creation of domestic engineering competence and the ability to adapt methods to specific organisations. The distinction between methodological invention and skilled implementation is necessary for any credible account of innovation.

Data quality emerged as a central problem when analytical platforms began integrating information from sources over which a single organisation had limited control. A dataset can be technically valid yet contain duplicated entities, outdated addresses, inconsistent measurement units or ambiguously defined categories. Poor quality propagates through a system because every subsequent transformation may preserve or amplify earlier defects. Rules for validation and reconciliation can identify many problems, but their design depends on knowledge of what the data are meant to describe. Commercial software developed in Prague increasingly addressed data profiling, master data management and governance in response to these needs. Ataccama, founded in Prague in 2008, became an example of an enterprise software company specialising in data quality and related management functions. Its product history demonstrates how locally developed engineering competence can enter international markets without implying that all underlying database principles originated in the company. The analytical lesson is that quality management must combine technology, stewardship and responsibility for definitions. When trustworthy information becomes a shared organisational resource, the people responsible for describing and correcting it become as important as the software that stores it. These concerns would later become particularly prominent when automated analytical systems depended on complex chains of reused data.

Government data created a related but distinctive set of opportunities and constraints for information research. Public authorities collect information for taxation, statistics, transport,

planning and other legally defined purposes, rather than primarily for commercial analysis. Publishing selected datasets as open data can enable independent research and new services, but this requires attention to legal limits and technical usability. Data that are nominally available can remain practically inaccessible if formats are inconsistent or metadata are incomplete. In Czechia, the development of public open-data practices encouraged discussion of machine-readable formats, catalogues and common vocabularies. A national catalogue can help users locate datasets, although catalogue registration does not automatically establish the quality or completeness of the underlying records. Opening public data also demands careful distinctions between aggregate information suitable for release and personal information requiring protection. Researchers interested in interoperability consequently faced both semantic and institutional questions about how independently maintained records could be connected. These issues illustrate a broader principle of public digital development: openness is valuable only when users can understand the meaning, limitations and permitted uses of published data.

Semantic integration of public information became an identifiable research direction in the work of Czech specialists concerned with linked data. The approach seeks to connect information through explicit identifiers and machine-readable relationships rather than relying solely on matching text labels. Two institutions may describe the same municipality using different names, administrative codes and classification systems. A consistent identifier and a documented mapping can make such records interoperable, provided the relationship is historically and administratively justified. Research associated with Prague, including work by Jakub Klímek and Martin Nečaský, examined questions of data modelling, publication and exchange in this environment. These investigations were connected with the broader international movement towards reusable, linked information on the web. They also exposed a persistent danger: joining datasets too aggressively can create false equivalences that appear authoritative once they enter automated pipelines. Documentation of provenance and reference vocabularies is therefore indispensable when public records are repurposed for analysis. The Czech experience demonstrates that the digital value of information depends as much on shared meaning as on its physical availability. Its contribution includes practical methods for improving interoperability within institutions whose administrative responsibilities remain separate.

Scientific research infrastructures presented a different challenge because the data they preserve must remain interpretable beyond individual projects. An experimental measurement is meaningful only if later users can establish how it was obtained, processed and related to an instrument or observation. The principles of Findable, Accessible, Interoperable and Reusable (FAIR) research data provide a widely adopted framework for managing such responsibilities. These principles do not imply that every scientific dataset should be publicly downloadable without restrictions. Instead, they encourage clear identification, documentation, appropriate access conditions and the use of formats that permit subsequent scientific work. Czech institutions participated in the development of the European Open Science Cloud initiative and established the national EOSC CZ programme, connected with the European Open Science Cloud (EOSC) to improve national research-data management. A 2024 overview by Matěj Antol and colleagues described plans for a national ecosystem supporting FAIR research data and the governance arrangements required for implementation. By 2025, the programme represented an

active institutional transition towards more coordinated stewardship, not a reason to assume that all Czech research data had already been harmonised. Its importance lies in connecting data management with the reproducibility and cumulative development of scientific knowledge.

The creation of shared research repositories also raises architectural questions that differ from those of an ordinary departmental database. Researchers need to preserve raw files, structured observations, analysis scripts and contextual descriptions across several generations of software. Object storage, geographically distributed infrastructure and consistent identifiers can make such preservation more resilient against equipment failure. However, replicated copies do not guarantee scientific validity if metadata are lost or if the history of transformations is undocumented. The National Repository Platform associated with EOSC CZ illustrates the emerging effort to provide common services for scientific datasets under Czech institutional responsibility. Documentation of the platform identifies distributed storage and repository software as components of this approach. Such infrastructure should be assessed according to its actual deployment at each date, since later expansions must not be projected backwards into the period before 2026. For researchers, the central question is whether deposited material can be discovered, interpreted and legitimately reused years after its original publication. The movement towards managed repositories therefore constitutes a change in scientific practice as well as an investment in technical equipment. It broadens the meaning of national digital infrastructure from processing capacity to the durable preservation of evidence.

The data-intensive sciences provide compelling examples of how specialised information management can change the questions researchers are able to ask. Biological laboratories generate sequences, images and measurements whose meaning depends on experimental context and standardised descriptions. Astronomical investigations rely upon large observational collections that must be searched through coordinates, times and physical characteristics. Materials researchers combine simulated properties with measurements collected under different experimental conditions. A common information problem in these settings is how to retrieve relevant evidence without requiring every research group to reconstruct an entire dataset manually. Czech computer-science groups contributed tools and methods for indexing, similarity search and large-scale information handling that could be adapted across disciplinary boundaries. At Masaryk University, work on searching biological and other complex structures illustrates the potential of methods originally developed for general retrieval problems. Such adaptation does not mean that one database technique solves the scientific questions of every discipline, because each type of evidence imposes its own validation requirements. The significant contribution is a reusable computational approach whose limits can be investigated within the standards of the receiving science.

Commercial analytics enterprises also contributed to the country's growing competence in managing information at organisational scale. GoodData was founded in 2007 by Czech entrepreneur Roman Staněk and developed an international business around analytics and business-intelligence software. Its international corporate organisation means that commercial success cannot simply be counted as a discovery produced within a Czech university. Nevertheless, the company's history illustrates how expertise connected with Czech software engineering could circulate through globally oriented products and engineering teams. Analytics

platforms sought to make complex transformations and reports accessible to organisations without requiring every user to manage database infrastructure directly. This convenience introduced new questions about consistent metrics, permission management and the provenance of displayed indicators. A report on sales performance, for example, becomes unreliable when different departments apply different definitions of a completed transaction. The engineering response involves controlled semantic models, integration procedures and mechanisms for reproducing calculations. The wider historical significance of enterprises such as GoodData lies in their contribution to a professional market for sophisticated data systems rather than in any unsupported claim of exclusive ownership of analytics methods. They also created professional pathways linking Czech programmers, data engineers and internationally distributed commercial organisations.

Keboola provides another instructive example of the movement from software services towards integrated data-processing platforms. The company emerged from Czech entrepreneurial activity in the late 2000s and increasingly concentrated on data integration and analytical workflows. Its early development involved practical difficulties in transferring information between different business applications and reporting tools. A data pipeline must reliably obtain material from a source, transform it into a usable representation and deliver it to an appropriate destination. The difficulty lies in maintaining this process as software interfaces, datasets and organisational requirements change. Keboola's published accounts describe how its direction developed from individual application projects towards a reusable platform for connecting and transforming business data. The case illustrates the commercial importance of data engineering, a field sometimes overshadowed by more visible predictive models. It also demonstrates why successful analytics depends upon mundane but demanding operations of monitoring, documenting and correcting data flows. For Czech technological development, such enterprises contributed practical expertise that complemented university research without being identical to it.

The growth of data-management companies increasingly shifted attention from individual datasets towards the lineage of complex analytical systems. Lineage describes the path through which an output can be traced back to originating records, processing steps and intermediate transformations. This information is necessary when organisations must explain why a result changed or identify which reports are affected by a defective source. Manta, a company with Czech technological roots, developed software concerned with automated data lineage and the analysis of dependencies. In October 2023, International Business Machines Corporation announced its acquisition of Manta Software as part of its data and artificial-intelligence governance activities. The transaction illustrates international interest in specialised information-management expertise associated with the Czech technology ecosystem. It should not, however, be interpreted as proof that the acquiring corporation's entire product portfolio became a Czech scientific achievement. Ataccama and other enterprise vendors similarly highlight the growing economic importance of information quality, classification and controlled processing. The shared historical pattern is the increasing commercial value of techniques that make complicated information systems transparent enough to audit and maintain. This pattern

becomes more consequential as automated decisions rely on data whose origins are otherwise difficult to establish.

Distributed data architectures introduced further constraints as organisations moved from central databases towards networks of cloud services and specialised storage systems. Distribution may improve availability and permit processing close to data sources, but it complicates consistency, security and failure recovery. When several services update related information independently, users can encounter contradictory results unless the architecture defines reconciliation rules. A system optimised for rapid transactions can have different requirements from one designed to analyse several years of historical records. Designers therefore choose among replication strategies, indexing approaches, processing frameworks and guarantees about the visibility of updates. Czech university teaching and research increasingly incorporated these issues, as illustrated by Masaryk University's courses on non-relational databases and distributed data processing. The spread of cloud services did not remove the fundamental importance of transaction logic or formal data models. Instead, it made system architecture more explicitly dependent upon the intended balance among performance, correctness and availability. Responsible evaluation must ask what a distributed system guarantees under network failure rather than assuming that a larger collection of servers is necessarily superior.

By the early 2020s, the interaction between data analytics and machine learning made the quality of underlying information still more consequential. A predictive model can learn patterns from millions of examples, but systematic errors in those examples can become embedded in its output. Training data may reflect historical inequalities, changing institutional practices or incomplete coverage of particular populations. An apparently accurate model can therefore perform poorly when applied to people or circumstances that differ from those represented in its training material. Data scientists must investigate sampling, documentation, uncertainty and the conditions under which a model is deployed. For Czech research and industry, these problems created opportunities for cooperation among statisticians, software engineers, domain specialists and experts in data governance. The ability to process unstructured information through learned numerical representations also returned attention to the retrieval questions long studied in Prague and Brno. Vector search can locate semantically related material, but the similarity of representations is not itself proof that a retrieved statement is correct. Reliable use requires evaluation, traceability and mechanisms for detecting changes in datasets or models. These requirements show why the future of data science depends upon strong information systems as well as advances in predictive algorithms.

The reproduction of expertise was an essential condition for the continuity of Czech research in databases and analytical methods. Charles University sustained programmes linking formal data modelling, software engineering and the investigation of novel database architectures. Masaryk University connected large-scale retrieval research with courses and laboratories that gave students access to experimental systems. The Institute of Information Theory and Automation preserved a complementary emphasis on statistical reasoning and uncertainty. Professional conferences and collaborative publications allowed researchers from these settings to test their ideas within international specialist communities. Industry created another route through which

graduates could encounter practical problems of data quality, interoperability and large-scale software operation. These interactions were valuable precisely because they did not dissolve distinctions between research, engineering and commercial delivery. A strong scientific school develops methods that other investigators can examine, whereas an enterprise must also meet obligations concerning service reliability and customer requirements. The Czech experience suggests that long-term competence emerges when these functions reinforce one another without being confused.

Between 1993 and 2025, Czech data science and database research developed through several overlapping intellectual and organisational transformations. The management of structured records remained indispensable even as information systems expanded towards documents, graphs, multimedia objects and distributed services. Prague contributed studies of XML integration, schema evolution and multi-model databases, while Brno developed internationally significant research on metric-space similarity search and scalable retrieval. Work at the Czech Academy of Sciences clarified the probabilistic foundations of reasoning from complex and uncertain information. Parallel developments in public data, scientific repositories and commercial platforms extended the consequences of these investigations beyond specialised laboratories. No single institution or technology can therefore be presented as the origin of the country's contemporary information economy. Its development resulted from accumulated expertise, international collaboration and the ability to connect conceptual advances with demanding practical environments. The most important unresolved challenges concern interoperability, reproducibility, responsible access, model validity and the preservation of meaning as information passes between systems. These challenges are not merely technical obstacles, since they determine whether automated conclusions can be trusted by scientists, managers and citizens. The Czech experience consequently demonstrates that the enduring innovation in data science lies not simply in possessing more information, but in creating defensible methods for converting information into knowledge.

Computer Networks, Internet Technologies, Cloud Computing and Distributed Information Systems

The development of computer networking in the Czech Republic between 1993 and 2025 illustrates how a specialised academic facility can become an essential component of national scientific capability. Networks did more than carry information between computers, because their architecture increasingly determined which kinds of collaborative research could be undertaken across institutional boundaries. A simulation may require processors in one city, experimental data stored in another and researchers working at several universities or laboratories. Making that arrangement dependable raises problems of routing, congestion, identity management, data integrity and operational responsibility that cannot be solved merely by installing faster cables. The Czech experience is especially instructive because universities

and public research organisations helped create the early national backbone before commercial internet services became widely available. Subsequent decades brought a layered infrastructure incorporating optical transmission, Internet Protocol (IP) connectivity, distributed computing, cloud services and shared scientific storage. These layers remained intellectually distinct even when users encountered them through a single research portal or institutional account. The most significant national achievements therefore include original technical development, organisational innovation and sustained participation in international networks, rather than connectivity figures considered in isolation. This chapter examines those achievements while distinguishing technologies developed within Czech institutions from internationally standardised methods adopted for local use.

The institutional origins of the modern Czech networking system precede the establishment of the independent republic. Czechoslovakia formally connected to the internet on 13 February 1992 at the Czech Technical University in Prague, following an earlier period of experimentation and academic communication. On 15 June 1993 the nationwide academic backbone known as CESNET began operation under the university's responsibility, linking the principal university centres of the new state. Its Prague–Brno connection initially offered 64 kilobits per second, a figure that indicates the modest transmission resources available at the beginning of independence. Other university towns were served through slower connections, so the network's immediate significance lay in establishing reach and professional competence rather than impressive bandwidth. The project helped create a community capable of administering intercity communication, exchanging technical knowledge and defining common expectations for connected institutions. Jan Gruntorád became closely associated with this process and later with the long-term direction of the CESNET association. Historical accounts published by CESNET show that the early backbone also carried some commercial traffic while a specialised private market was still emerging. This mixed arrangement was transitional rather than the permanent organisational model of Czech research networking. It nevertheless demonstrated that academic investment could establish technical foundations subsequently used by a much wider information society.

The creation of the CESNET association in 1996 gave the national research and education network (NREN) a more durable organisational basis. Universities and the Czech Academy of Sciences established a cooperative structure able to maintain advanced connections independently of a single faculty or ministry department. This was important because networking services require shared governance over decisions whose consequences reach far beyond the institution purchasing an individual device. The association initially operated academic and commercial activities through distinct arrangements inherited from the network's formative years. In 2000 it separated its commercial network from the research infrastructure, clarifying the different purposes of market connectivity and publicly supported scholarly communication. Academic institutions needed predictable capacity for scientific collaboration, while commercial operators increasingly competed on price, reach and customer services. The distinction also allowed the association to concentrate on applications whose technical demands could not always be justified through ordinary telecommunications contracts. Its subsequent work therefore combined professional network operation with experimental development in

communication technologies, security and scientific services. The organisation's published chronology identifies this combination as a central feature of its evolution rather than a late addition to an otherwise conventional internet provider.

Backbone modernisation during the 1990s and early 2000s transformed both the capacity and the physical organisation of Czech academic communication. After the initial leased-line network, participation in the European TEN-34 initiative created conditions for a backbone operating at 34 megabits per second from 1997. The subsequent TEN-155 arrangements reflected a broader European movement towards higher-capacity academic transport and more systematic cross-border connection. CESNET's chronology records the Prague–Brno route reaching 2.5 gigabits per second in 2000, an extraordinary change compared with the early 1993 configuration. The CESNET2 generation, introduced during the following period, increasingly relied on fibre infrastructure rather than treating transmission solely as a purchased telecommunications service. Fibre gave network engineers greater control over the relationship between the optical medium, equipment and the channels made available to connected institutions. Dense Wavelength Division Multiplexing (DWDM) made it possible to transmit several optical signals through the same fibres at different wavelengths. This approach increased useful capacity without requiring a completely separate physical route for every scientific service. The technological consequences were accompanied by organisational obligations concerning route diversity, maintenance and long-term investment. In that sense, the transition to optical networking converted the research backbone from a shared connection into a strategically managed technological infrastructure.

The internet architecture carried by the backbone depended upon standards shared with networks throughout the world. Transmission Control Protocol (TCP) provided dependable end-to-end transport for many applications, while IP made communication across heterogeneous networks possible. The layered architecture permitted Czech researchers to use international scientific software without requiring every network operator to implement the same proprietary systems. Nevertheless, the apparent universality of the protocols concealed demanding tasks involving address allocation, routing policy and the behaviour of interconnected organisations. Border Gateway Protocol (BGP) exchanges information about reachable networks between independently administered routing domains, making it central to the wider internet's connectivity. Its configuration requires attention to filtering, route legitimacy and resilience because mistaken announcements can disrupt communication beyond a single campus. Operators therefore needed both engineering competence and participation in professional communities that exchanged experience about failures and preventive controls. The Czech national backbone served as an environment in which these organisational and technical practices could mature alongside growing traffic. The history is consequently not one of inventing TCP or BGP in Czechia, but of developing the expertise necessary to operate and improve complex systems based upon them.

Domestic internet exchange and domain administration formed complementary components of Czech network development. The creation of NIX.CZ in 1996 offered internet operators a shared setting for exchanging traffic without unnecessarily sending domestic communication through distant transit providers. Such an internet exchange point (IXP) can reduce latency, conserve

international capacity and encourage operational cooperation among otherwise competing networks. The CZ.NIC association, established in 1998 to administer the national .cz domain, developed another essential component of internet reliability. Its responsibilities concern the Domain Name System (DNS), through which domain names are associated with the technical information needed to locate online services. Unlike a straightforward commercial portal, the domain registry forms part of critical shared infrastructure whose failure would affect many unrelated organisations. The later development of Knot DNS within CZ.NIC laboratories illustrates how operational needs could stimulate original open-source software engineering. CZ.NIC introduced this authoritative name-server project publicly in 2011, and by 2021 used it for generating and signing the .cz zone. The example helps distinguish a nationally developed internet infrastructure technology from the international protocols with which it interoperates. It also shows that institutional arrangements supporting network stability can become sources of software innovation.

The transition between successive versions of the Internet Protocol illustrates the importance of long-term architectural adaptation. Internet Protocol version 4 (IPv4) remained indispensable, but its finite address space created growing constraints as connected devices and services multiplied. Internet Protocol version 6 (IPv6) provided a much larger address space and additional possibilities for network configuration and operational design. CESNET experimented with the newer protocol during the 1990s and records its deployment in the CESNET2 production environment by 2003. The transition required more than replacing numerical address formats because routing, security, monitoring and institutional applications had to function under changed conditions. Dual-stack operation allowed many organisations to maintain IPv4 services while gradually introducing IPv6 to users and equipment. Such coexistence also introduced additional management work, since differences between the two protocol environments could generate unexpected failures or security gaps. By participating in the transition early, the Czech academic network provided practical experience that other organisations could use when preparing their own infrastructures. This episode demonstrates that technological innovation sometimes consists of mastering the adoption of an international standard rather than originating that standard nationally.

Optical communication became a particularly distinctive field of technical development within CESNET. Ordinary packet forwarding takes place above a physical transport layer whose capacity, signal quality and switching characteristics ultimately constrain scientific communication. During the early 2000s, CESNET began developing the CzechLight family of optical equipment in response to requirements that available commercial systems did not always meet economically or operationally. These devices addressed practical problems such as remote management of optical amplification and the configuration of transmission paths over leased dark fibre. An important objective was to maintain advanced backbone services while avoiding dependence on inflexible proprietary components for every modification. The work connected optical engineering with software control, demonstrating that management functions could be as important as raw transmission performance. Slavíček and Vojtěch described the CzechLight equipment family in a 2010 conference paper, linking its design to requirements encountered on the national backbone. Subsequent developments extended this engineering

effort towards remotely programmable devices and more sophisticated reconfiguration of optical channels. The achievement should be understood as an identifiable contribution in communication engineering rather than as the invention of fibre-optic networking itself. Its wider value lay in turning the particular needs of a national scientific network into reusable technological expertise.

Research on software-defined optical networks made these engineering questions still more explicit during the following decade. Software-Defined Networking (SDN) separates aspects of network control from the underlying forwarding equipment, allowing more systematic configuration and adaptation. Applied to the optical layer, the approach raises difficult questions about the programmability of wavelengths, amplification, switching and the interfaces connecting software to physical devices. Kundrát, Radil, Altmannová and their collaborators investigated these possibilities using CzechLight technology within the operating CESNET network. Their 2015 study described an upgrade of the Cheb node using reconfigurable optical add-drop multiplexers (ROADMs), showing how remotely controlled components could replace less flexible arrangements. The research connected demonstrable operational improvements with a broader architectural argument about programmable transmission infrastructure. Its significance lies partly in the ability to alter optical channels without requiring an engineer to visit every remote physical site. The case also illustrates the advantages of conducting network research in an operational environment where robustness and maintainability can be tested against real constraints. A laboratory demonstration alone would not establish the same evidence about sustained service under production conditions.

The CESNET3 generation represented another substantial transformation in the period approaching 2025. Modernisation across the national backbone introduced more flexible optical transport arrangements and transmission channels capable of carrying up to 400 gigabits per second. The 2023 account of the completed upgrade described a network whose design could accommodate further advances without replacing its entire physical geography. Higher channel capacity mattered especially for scientific facilities that regularly exchange very large observational or experimental datasets. Nevertheless, the useful effect of faster transmission depended upon complementary improvements in routing, computing access, storage and the applications generating network traffic. In December 2024 CESNET reported successful testing of coherent 400-gigabit transceivers across an 846-kilometre optical route under defined operational conditions. The test evaluated an implementation option that could reduce reliance on additional transponder equipment when connecting distant network devices. It should not be confused with a claim that every Czech institution possessed a dedicated 400-gigabit service or that all traffic experienced this speed. The distinction between maximum channel capability, experimentally validated performance and ordinary user throughput is necessary for a scientifically defensible history. By 2025, the backbone had become a platform for specialised experiments as well as an increasingly capable communications utility.

European integration was fundamental to the purpose and practical value of the Czech academic network. No national backbone can provide international research connectivity alone, because scientific collaborators and large experimental facilities operate across numerous independently managed jurisdictions. The earlier TEN-34 and TEN-155 connections prepared the institutional

basis for participation in the pan-European GÉANT networking collaboration. GÉANT links national research and education networks through shared backbone infrastructure and coordinated services while preserving national responsibilities for local institutions. This arrangement allows Czech universities to participate in projects requiring access to European laboratories, data resources and computing facilities. It also supports specialist services that would be difficult or unnecessarily expensive for each university to procure independently. Cross-border cooperation involves technical alignment in addition to formal membership, including routing, monitoring, incident handling and service assurance. GÉANT's description of the European research-networking model makes clear that a user's end-to-end connection commonly passes through several administrative domains. The quality of international communication therefore depends on cooperation among operators rather than the sophistication of one country's backbone in isolation.

Direct connections with neighbouring academic networks strengthened the Czech Republic's position within Central European research geography. Links with Austria's ACOnet, Slovakia's SANET and Poland's PIONIER provided complementary routes for communication and international collaboration. These relationships are particularly important when research projects combine regional university groups or depend upon access to neighbouring scientific facilities. Redundant paths can also mitigate the consequences of an interruption on a particular international route, although resilience depends upon whether the paths are physically independent. The presence of several cross-border connections does not automatically eliminate a shared point of failure in optical ducts, equipment rooms or power supply. Network planners must therefore evaluate geographic diversity, recovery procedures and the practical limitations of the contracted transmission infrastructure. CESNET's published description of CESNET3 documents its connections with partner networks and exchanges, providing evidence of the system's multi-directional architecture (CESNET, n.d.-b). The resulting topology supports international integration while preserving opportunities for direct regional traffic exchange. It also illustrates how network resilience emerges from design choices that are not fully expressed by headline transmission speeds. For Czech research, these arrangements made international cooperation more continuous and less dependent upon a single gateway to the wider world.

Some scientific applications place extraordinary demands upon the timing and predictability of data transmission. Particle physics, astronomy and large experimental collaborations may require transfers whose aggregate volume exceeds what conventional office connectivity could manage efficiently. Czech participation in experiments at the European Organization for Nuclear Research (CERN) gave special relevance to dependable links serving internationally distributed data analysis. The development of the Large Hadron Collider Open Network Environment provided a specialised setting for transferring scientific information among participating facilities. CESNET records its connection to this environment in 2013, an event that further embedded Czech research networking within a global experimental system. Such networks depend on accurate traffic engineering and careful coordination between storage and processing resources. A high-speed path offers little practical benefit if the receiving storage service cannot ingest information at a matching rate or if transport protocols are poorly tuned. The scientific significance therefore resides in the combined capability of networks and laboratories rather than

the capacity of a single backbone interface. Research infrastructures increasingly became components of an internationally distributed workflow rather than isolated sites connected only for occasional exchange.

Advanced optical networks also created opportunities to distribute forms of scientific information other than conventional internet packets. Precise time and frequency transfer is essential for experiments that require synchronised measurements or the comparison of highly stable reference signals across distant laboratories. Optical-fibre infrastructure can carry such signals under demanding technical conditions, provided that propagation delays and environmental disturbances are carefully controlled. CESNET's research activities included optical time transfer between Prague and Vienna as well as later experiments using advanced synchronisation technologies. Its 2024 annual report describes applications of the White Rabbit system and experiments involving quantum key distribution alongside high-speed data transmission. Quantum key distribution seeks to establish shared cryptographic keys using quantum physical processes, but it is not a replacement for every component of ordinary network security. The research significance lies in understanding coexistence, interference, equipment requirements and feasible operating conditions on shared fibre. These developments connect computer networking with photonics, metrology and quantum communication without erasing the different scientific principles involved. They also show why a national research backbone can serve as experimental infrastructure for disciplines far beyond telecommunications engineering. The Czech contribution is most accurately located in tested systems, operational methods and internationally shared technical experience rather than in claims of exclusive ownership of quantum communication.

A national scientific network becomes useful only when researchers and students can reach its services through practical institutional arrangements. The eduroam initiative provides a prominent example by enabling individuals from participating educational organisations to obtain network access when visiting other member institutions. CESNET introduced eduroam within the Czech academic network in 2004 and subsequently supported its wider use. The underlying principle depends upon authentication through the user's home institution rather than the creation of a separate local account at every destination. Roaming therefore translates institutional cooperation into a routine experience for visiting researchers, lecturers and students. It also introduces requirements for secure credential handling, federated trust and coordination when a user encounters a connectivity problem abroad. The same distributed logic influenced national academic identity federations and the management of authorisation across institutional boundaries. By reducing administrative barriers to mobility, these services complemented the international connections of the physical network. They demonstrated that the effectiveness of research infrastructure can depend as much on identity and trust as on the transmission of data.

Federated identity management developed further as scientific applications became distributed across universities, laboratories and international projects. A common difficulty arises when a researcher belongs to a home university but needs access to computing resources administered by another organisation. Simple authentication establishes an identity, whereas authorisation determines which resources that identity is permitted to use under particular conditions. If every

service maintains an unrelated account database, both administrative errors and difficulties in revoking access become more likely. The Perun Authentication and Authorisation Infrastructure (AAI), developed by CESNET and Masaryk University, addresses these problems through coordinated management of users, groups and service entitlements. Its architecture can connect institutional identity providers with the management requirements of research collaborations extending across national boundaries. Interoperability with international identity federation mechanisms gives the system relevance beyond a closed Czech institutional environment. The important technical achievement is not merely offering a convenient login page, but synchronising identities and permissions in systems whose underlying administrators have different responsibilities. CESNET's description of Perun identifies its role in virtual research organisations and its connection with the international eduGAIN federation. This development illustrates how trustworthy networking depends upon protocols, institutional governance and software for expressing access policy consistently.

Security monitoring became increasingly important as the academic network grew in capacity and exposure to external threats. High-speed links create opportunities for scientific collaboration, but they also increase the scale at which malicious or mistaken traffic can affect shared systems. Traditional inspection methods may become impractical if they require storing or examining every packet in detail across the entire backbone. A more scalable approach uses network-flow records that summarise communication characteristics while retaining information useful for anomaly detection. The Network Measurements Analysis framework (NEMEA), developed by researchers associated with CESNET and Czech Technical University, exemplifies this method. Tomáš Čejka, Václav Bartoš, Marek Švepeš, Zdeněk Rosa and Hana Kubátová presented the modular framework in a peer-reviewed conference paper in 2016. The architecture was designed for stream-oriented analysis and practical operation on high-speed research-network connections, with modules that could be extended for different detection tasks. Its originality lies in an identifiable software architecture for operational traffic analysis rather than the general invention of flow monitoring. The system illustrates productive interaction between university research and the challenges encountered by a national backbone operator.

The broader security architecture of Czech research networking combined monitoring, institutional response and the exchange of incident information. CESNET established specialised security teams and services as cyberattacks became more automated and their consequences more disruptive. Services such as Warden and Mentat supported the sharing and analysis of security-event information across participating systems. A monitoring system is useful only when analysts can interpret findings and coordinate appropriate action with the organisations affected. The network's operators therefore needed procedures for incident classification, notification, escalation and the handling of potentially sensitive records. At the national level, cooperation with CZ.NIC and other cybersecurity institutions helped place academic security within a wider professional environment. The complexity increased when services extended to research hospitals, scientific repositories and specialised laboratories with different operational risks. Security policies also had to recognise that scientific openness cannot be reduced to unrestricted access, particularly where confidential data or critical instruments are involved. The resulting research and operational culture linked automated analysis with human judgement

rather than treating either one as sufficient. That interaction remains a significant component of national capacity to maintain trustworthy distributed systems.

Distributed computing expanded the role of Czech academic networking from communication between machines to coordinated use of their processing resources. The MetaCentrum initiative, incorporated into CESNET in 1998, provided an institutional foundation for connecting computing facilities that were owned and operated by different participating organisations. Grid computing rests on the idea that a collection of heterogeneous computers can undertake appropriately organised workloads through common access and scheduling arrangements. Such a system is not equivalent to one physically unified supercomputer, because participating nodes may have different processors, local software and usage restrictions. Users submit computational jobs that are assigned to available resources according to operational policies and the characteristics of the requested tasks. Researchers can thereby gain access to capacity beyond the workstation or laboratory cluster directly administered by their own department. Scientific fields with many independent calculations are particularly well suited to this model, although applications requiring intense communication between processes pose greater difficulties. The grid's development thus demanded both distributed systems engineering and a stable organisational framework for sharing public research resources. Its importance in the Czech setting lies in creating a national computing service through cooperation rather than relying only on individual institutional acquisitions.

Resource scheduling emerged as a central technical challenge for shared grid environments. A job management system must reconcile users' requests with resource availability, expected run times, memory requirements and the policies adopted by participating institutions. Fair-share approaches can prevent sustained monopolisation by a small number of users, but they also involve explicit choices about scientific priorities. An apparently idle machine may not be immediately suitable for a task that requires a particular operating environment, accelerator or large block of memory. Data location further affects placement decisions when transferring inputs would take longer than the calculation itself. Researchers working on MetaCentrum and related Czech infrastructures investigated monitoring, accounting and interoperable job submission as the service evolved. Published material from the MetaCentrum community documents conference contributions on resource monitoring and the practical interaction of grid and cloud services. These developments demonstrate that distributed computing is not simply a matter of adding processor counts across institutions. Effective resource sharing depends on reproducible procedures, trustworthy accounting and a reasonably predictable experience for scientists with different levels of technical expertise. Its methodological relevance extends into contemporary platform engineering, where resource allocation remains a fundamental problem.

Cloud computing introduced another model for delivering shared information technology resources to scientific users. Instead of submitting only individual jobs to a scheduler, users could obtain virtual machines, configure software environments and deploy services resembling infrastructure normally controlled by local administrators. Infrastructure as a Service (IaaS) describes this provision of virtualised processing, networking and storage through interfaces that permit user-directed configuration. The approach can be valuable for scientific applications requiring specialised libraries, continuous web services or data-processing pipelines that do not

fit conventional batch scheduling. CESNET's chronology records the introduction of MetaCloud services in 2012, while subsequent Czech research addressed the compatibility of cloud infrastructures using different management systems. The MetaCentrum publication record includes work by Boris Parák, Zdeněk Šustr and collaborators on the Ruby implementation of the Open Cloud Computing Interface (rOCCI) and cloud interoperability during 2014. Their subject was not the invention of virtualisation but the practical difficulty of managing resources through consistent interfaces across independently operated clouds. These investigations belonged to wider European Grid Infrastructure discussions in which national providers sought common methods for offering computing services. The Czech contribution therefore combined operational deployment with documented research on cloud interfaces and federation.

The growth of the CERIT Scientific Cloud (CERIT-SC) at Masaryk University expanded opportunities for experimental cloud and data-intensive research. A conventional institutional cluster may provide compute nodes under fixed centrally administered conditions, whereas a scientific cloud can permit researchers to create more elaborate virtual environments. This flexibility can be essential when an application combines persistent databases, automated processing services and temporary computational workers. Virtualisation allows multiple logical systems to share physical hardware, although the resulting efficiency depends upon workload behaviour and adequate resource isolation. Container technologies later offered another means of packaging applications consistently without creating a complete virtual machine for every component. CERIT-SC developed its role as an infrastructure partner that could adapt computing environments to research domains rather than limiting users to a single standard configuration. Its services became especially relevant for data-rich disciplines, including life sciences, where workflows may require careful management of specialised software and intermediate datasets. The centre's institutional account presents this user-oriented, experimental function as complementary to the national network and the IT4Innovations supercomputing centre. The broader significance is the movement from shared equipment towards supported digital environments in which complex investigations can be designed and maintained. Such development also required expertise in automation, user support and the security of interconnected services.

Grid, cloud and supercomputing services remained distinct even as they became more closely integrated within the Czech research ecosystem. A supercomputer is typically organised to deliver high computational performance through tightly coordinated processors and specialised communication architecture. A grid may aggregate more heterogeneous resources across administrative domains while accepting corresponding differences in latency and configuration. A cloud offers greater user control over software deployment and virtual network configuration, potentially at the expense of some performance predictability. These distinctions matter because a large simulation involving frequent process-to-process communication may need a different platform from an online analysis service or a population of independent jobs. Consequently, a national digital infrastructure cannot be evaluated satisfactorily through aggregate processor counts or generic promises that all work will run faster. Researchers and platform architects instead identify the behaviour of each workflow, including its communication, storage and reproducibility requirements. The e-INFRA CZ service documentation recognises this

differentiated portfolio through separate options for batch computing, supercomputing, virtualised clouds and container platforms. Integration is most effective when users can move between these options without losing the specific guarantees that make each appropriate for its intended scientific purpose.

Scientific storage systems became another major component of the transition towards integrated digital research services. Large experimental instruments, imaging equipment and simulations generate datasets whose significance may extend far beyond the duration of the original project. A distributed storage system can replicate information across facilities, separate high-speed working space from longer-term retention and provide access to researchers at different locations. However, adding storage devices does not automatically solve the problems of data integrity, provenance, controlled access or the costs of maintaining material over time. Researchers need to know whether their files have been transferred completely, which version is authoritative and what will happen if an individual storage site becomes unavailable. CESNET expanded its national storage services during the 2010s and 2020s as demand for shared data capacity increased. Its published chronology records capacities exceeding 100 petabytes of gross storage in 2022 and additional facilities commissioned in Brno and Dolní Břežany in 2024. Gross capacity is not the same as storage available to end users after replication, protection and system overhead have been accounted for. A scientifically responsible account therefore distinguishes nominal hardware scale from the durability and accessibility of research data. The historical achievement lies in the establishment of an institutional service able to support data-intensive science across many research organisations.

Distributed data management also required software capable of coordinating files and permissions across heterogeneous storage locations. Research communities increasingly needed more than simple downloads, especially when datasets were large, processing was repeated and collaborators operated at different institutions. Systems such as Onedata were developed to support common access and data management across otherwise separate underlying resources. The difficulty is not only moving bytes, but describing a coherent relationship between file names, physical locations, metadata and the operations performed on the data. Svoboda and colleagues presented Onedata4Sci in 2023 as a prototype approach to life-science data management, covering acquisition, access, processing and archiving. Their work considered applications in plant imaging, cellular imaging and cryo-electron microscopy, which place different demands on data organisation and computing workflows. The project demonstrated how a broadly applicable infrastructure could be adapted to specific scientific communities without simply imposing one rigid research procedure. Its significance lies in connecting distributed-systems development with identifiable research requirements rather than treating storage interoperability as a purely administrative concern. Such approaches became increasingly relevant as reproducible scientific workflows required cooperation between networking, cloud and data-management specialists.

Real-time multimedia communication provided a further field in which Czech research-network expertise generated specialised technical solutions. Scientific collaboration often requires the transmission of images, audio or visualisations whose timing requirements are not well described by the size of their files alone. Conventional conferencing can tolerate some delay, but

interactive musical performances or certain remote scientific demonstrations demand substantially tighter synchronisation. CESNET developed UltraGrid technologies and later approaches associated with its Modular Video Transmission Platform (MVTP) to address demanding audiovisual use cases. The technologies explored compression, packet handling and low-latency communication under conditions where the quality of interaction mattered as much as raw video resolution. Practical applications included remote collaboration, cultural presentations and the transmission of high-definition scientific visualisation between distant sites. CESNET's institutional chronology records high-definition and ultra-high-definition demonstrations as well as recognition received for the MVTP development. The important point is not that Czech researchers invented video conferencing in general, but that they produced identifiable systems suited to demanding professional scenarios. These projects show that research networking can create innovations whose usefulness is felt outside academic computing laboratories. They also demonstrate the productive relationship between practical user requirements and the experimental refinement of transport technologies.

The creation of e-INFRA CZ marked an important institutional consolidation in the period approaching 2020. The initiative united CESNET, CERIT-SC and the IT4Innovations National Supercomputing Center in a coordinated national research infrastructure. Its establishment did not mean that the constituent organisations became identical or ceased to maintain their own areas of expertise. Instead, the arrangement sought to combine complementary strengths in networking, flexible scientific clouds, specialised computation and data services. Preparatory cooperation had been developing before the formal launch, including the submission of a joint project in 2019. The integrated infrastructure began operating in 2020 and provided a clearer organisational framework for services that individual research teams previously had to assemble through separate arrangements. The institutional significance was particularly important for smaller research groups without the resources to build extensive digital environments independently. The IT4Innovations account of the initiative emphasises that integration built upon already existing national infrastructures rather than replacing them with a wholly new scientific establishment. This approach illustrates how the consolidation of scientific services can itself constitute a meaningful innovation in research organisation.

The integration of networking, computation and storage also improved the conditions for participation in European research infrastructures. European projects often involve datasets that must remain usable across countries while obeying different institutional obligations concerning access, security and documentation. Connections through GÉANT and participation in the European Grid Infrastructure supported cross-border availability of research resources. The European Open Science Cloud (EOSC) added a complementary emphasis on making scientific data and services findable, accessible and reusable under appropriate conditions. These aims are frequently summarised through the principles of Findable, Accessible, Interoperable and Reusable (FAIR) research data. FAIR principles do not require unrestricted publication of every dataset, because ethical constraints, commercial confidentiality and legal obligations may justify controlled access. They instead encourage descriptions and technical interfaces that make responsible discovery and reuse more feasible. The development of the national EOSC CZ initiative during the early 2020s connected these European aims with Czech data repositories and

research-support organisations. Networking thus became part of a broader system of data stewardship rather than merely a means of transferring completed files. The resulting opportunities depended upon cooperation between computer scientists, librarians, legal specialists and the disciplinary researchers who understood the scientific meaning of the material.

The growing maturity of the Czech digital research system also made its structural vulnerabilities more apparent. More integrated services create benefits through shared access and common administration, but a failure in one widely used component can affect many research communities simultaneously. Cloud control systems, identity providers, storage directories and routing equipment may each become points at which organisational and technical risks intersect. Resilience therefore requires redundancy, tested recovery procedures, clear responsibility and realistic assumptions about how long interruptions might last. Cybersecurity introduces further complications when researchers exchange material through international collaborations with different legal and operational requirements. Long-term expenditure also matters, since optical equipment, energy-intensive data centres and specialist personnel demand stable support after construction grants have ended. Environmental considerations encourage more efficient systems and careful decisions about whether processing should occur locally, centrally or near an existing dataset. A national network's strategic value consequently depends on maintaining services as well as demonstrating occasional technical records. The Czech experience provides an example of infrastructure maturity in which operational reliability becomes inseparable from scientific ambition.

The period from 1993 to 2025 reveals a cumulative development from basic academic connectivity towards an integrated network of scientific services. The original CESNET backbone established institutional communication before the national internet market was fully developed, while later optical infrastructure provided increasingly capable transport for specialised scientific applications. National research groups contributed identifiable methods and software for optical-network control, traffic monitoring, cloud interoperability and the management of distributed data. The work of CESNET, Czech Technical University, Masaryk University, CERIT-SC, IT4Innovations and other partners demonstrates the value of cooperation among institutions with complementary strengths. European connections extended that national capacity by integrating researchers with facilities, expertise and professional communities beyond the country's borders. At the same time, the distinction between operating a global standard and creating an original technical contribution remained essential to evaluating historical achievements. The most meaningful measures include reproducible research results, sustained availability, the accessibility of specialised resources and the ability to preserve trustworthy data across institutions. No individual advance in transmission speed can substitute for those wider conditions of effective scientific collaboration. By the end of 2025, Czech computer networking had become both an important field of applied research and a foundational resource through which many other sciences could undertake ambitious projects. Its history demonstrates how technological progress arises when infrastructure, engineering knowledge, international cooperation and institutional responsibility develop together.

Software Engineering, Programming Technologies, Formal Verification and Reliable Computer Systems

The history of software engineering in the Czech Republic between 1993 and 2025 cannot be reduced to the appearance of successful applications or internationally marketed programming tools. Software engineering studies how complex software is specified, designed, implemented, tested, deployed and maintained under conditions in which requirements and operating environments continually change. Its intellectual problems differ from those of theoretical computer science because mathematical correctness must be connected with programming languages, organisational decisions, human activity and the limitations of real machines. They also differ from the concerns of the general software market, where commercial success may arise from effective distribution, timely product design or customer support without a corresponding scientific discovery. Independent Czechia inherited substantial expertise in programming, mathematical logic, computer architecture and industrial automation, but these capabilities entered a newly competitive technological environment after 1989. During the following decades, developers increasingly confronted modularity, interoperability, concurrency, system reliability, security and the coordination of large codebases maintained by geographically dispersed teams. Research groups in Prague and Brno contributed methods for describing component behaviour, verifying programs and analysing failures, while locally based enterprises developed influential tools for professional programmers. The interaction of these research and industrial pathways illustrates how a national software ecosystem can contribute to international engineering practice without claiming ownership of every technology used within its borders. This chapter therefore examines identifiable Czech contributions and their methodological significance, while recognising the continuing importance of international collaboration, open standards and technologies developed elsewhere.

The transformation of software practice began before the independent Czech state was established, since the political opening after 1989 changed how programmers obtained tools and exchanged ideas. Under state socialism, computing had developed through research institutes, technical universities and enterprise computing departments, often under conditions of constrained equipment supply and limited access to foreign products. Many specialists nevertheless possessed strong mathematical training and extensive experience with the practical demands of industrial information systems, control software and scientific computation. The emergence of private enterprises created new incentives to develop software as a product rather than merely as a component of centrally administered technical activity. International standards, commercially distributed operating systems and networked development environments entered professional practice alongside programming approaches already familiar to academic specialists. The transition was uneven because educational resources, computing hardware, financial investment and connections with foreign companies differed substantially across institutions and regions. By the mid-1990s, universities increasingly combined programming education with active research on software architecture, formal specification and the construction of reliable systems. Small enterprises also demonstrated that a technically coherent product could be created with relatively modest initial capital, although international distribution required commercial skills not normally taught in engineering courses.

The distinction between technological independence and intellectual isolation was particularly important, since Czech development increasingly relied upon globally maintained languages and interfaces while producing original extensions and tools. This combination of inherited expertise and institutional opening provided the foundation for later cooperation between academic software research, open-source communities and professional development organisations.

The origins of NetBeans offer one of the clearest historical examples of a locally initiated development tool acquiring international influence. According to the Apache NetBeans project's history, the initiative began in 1996 as Xelfi, a Czech student undertaking to construct a Java integrated development environment (IDE) using Java itself. The early team pursued an editor and programming workspace at a moment when both Java and its development-tool ecosystem were still rapidly evolving. The project grew beyond a classroom experiment when the developers began considering commercial distribution and cooperation with an entrepreneur prepared to support further work. Its architecture increasingly embraced modules and extensibility, making the resulting platform relevant not only to programming editors but also to other desktop applications. Sun Microsystems acquired the company in 1999, and NetBeans subsequently became an openly developed project with a substantial international community. This trajectory should be interpreted carefully because an international acquisition changed the ownership and institutional context of the product without erasing the original Czech contribution. The software's historical significance lies particularly in demonstrating the technical possibilities of modular development environments and the transfer of student engineering work into a global platform. It also shows that innovation in software engineering can concern the tools and architectures through which other programmers create software, rather than only the applications delivered to end users.

NetBeans illustrates a broader methodological issue: a programming environment is simultaneously a software product and an experiment in the organisation of development work. An integrated development environment brings editing, compilation, debugging, navigation and project administration into an interaction model intended to reduce the cognitive cost of programming. The modular architecture of NetBeans allowed extensions to be introduced without replacing the whole application, thereby presenting a practical example of separation between stable services and specialised functionality. Interfaces between modules become contracts whose stability affects maintenance, compatibility and the feasibility of independent third-party development. A tool may appear successful when a particular feature operates correctly, yet its deeper engineering quality depends on how future changes can be accommodated without destabilising other features. The NetBeans experience therefore demonstrates why architectural extensibility and application programming interface (API) design are important subjects of engineering research, not merely implementation details. The availability of source code under open licences also changes the ways defects are reported, extensions are reviewed and engineering knowledge circulates internationally. At the same time, community governance introduces demands for transparent decision-making, documentation and predictable release practices that differ from those of a small student team. By moving through commercial ownership and later foundation-based governance, NetBeans revealed both the advantages and the organisational complexity of maintaining shared software infrastructure.

Its Czech origins matter because they identify a formative technical contribution, whereas its subsequent history makes clear that such a contribution can develop through cooperation far beyond its place of origin.

A more explicitly scientific strand of Czech software engineering developed at Charles University through research on software components and their behavioural compatibility. In component-based engineering, a system is assembled from units whose offered and required services must be specified sufficiently clearly for independent development and subsequent integration. Simple agreement about method names or data formats cannot guarantee that two components will interact correctly when the order of operations matters. František Plášil and Stanislav Višňovský addressed this difficulty in their study of behaviour protocols for software components, published in IEEE Transactions on Software Engineering in 2002. Their work examined how descriptions of permitted interactions could support the analysis of compatibility and expose failures that would be invisible at the level of static interfaces alone. This distinction is important for systems in which one component expects messages, responses or state transitions in a particular sequence while another follows a different sequence. Behavioural specifications create an opportunity to detect certain integration problems before the complete system is deployed under operational conditions. The contribution is therefore not the invention of component-based programming itself, but a rigorous treatment of a specific engineering problem arising when independently constructed components must cooperate. Such research exemplifies the capacity of Czech academic groups to develop general methods rather than simply demonstrate another implementation of internationally established ideas.

The Prague component-research tradition subsequently extended beyond pairwise compatibility towards the organisation of complex software architectures. Tomáš Bureš, Petr Hnětynka and František Plášil described SOFA 2.0 in 2006 as a hierarchical component model intended to reconcile advanced architectural features with disciplined software construction (Bureš et al., 2006). The framework treated components as elements of a larger structure in which interfaces, deployment choices and communication mechanisms needed to be coordinated coherently. Hierarchy makes it possible to understand a complex application through successive levels of abstraction rather than by examining every class and procedure simultaneously. The modelling of deployment also matters because an architectural design that appears sound on paper may behave differently when its components are distributed across machines or execution environments. The SOFA research programme thus joined concepts from software architecture, modelling and runtime systems instead of treating components as isolated programming conveniences. An important methodological consequence was the possibility of relating architectural descriptions to tools used during implementation, configuration and execution. The framework's significance should nevertheless be assessed against its research objectives and published results rather than through unsupported claims of universal industrial adoption. Its sustained development demonstrates how a Czech scientific school pursued a distinctive line of inquiry into the long-term manageability of modular software. The broader lesson is that dependable software construction requires explicit architectural assumptions and mechanisms for checking whether implemented behaviour remains consistent with those assumptions.

The SOFA 2 research was also associated with model-driven development, an approach that treats abstract representations as working artefacts within software production. A model is valuable when it captures properties of a system that can be analysed, transformed or checked independently of incidental implementation choices. In practice, developers must decide which details are essential at a particular level and which can safely be postponed to subsequent design stages. Models become especially difficult to maintain when program changes are introduced without updating the corresponding architectural descriptions. Research into metamodels and component deployment therefore sought to establish coherent relationships between representations, configurations and executable components. The Czech contribution is visible in the continuity of work by Plášil, Bureš and Hnětynka on component frameworks and development methods, rather than in any single visual modelling notation. Malohlava, Hnětynka and Bureš later discussed the SOFA 2 ecosystem as a coordinated set of architectural and development facilities, including domain-oriented adaptations. Their work illustrates why apparently abstract modelling questions can influence practical tasks such as assembling a system, replacing a module or selecting a deployment configuration. The limitations of model-driven methods remain equally important, since a highly elaborate modelling infrastructure can impose costs that are disproportionate to the size or stability of an application.

During the 2010s, research at Charles University increasingly confronted software environments in which component relationships could not remain fixed throughout a system's lifetime. Autonomous devices, mobile services and cyber-physical installations may enter or leave a network, change their operational roles or lose communication unexpectedly. The Dependable Ensembles of Emerging Components (DEECo) project explored how adaptable components could form temporary groups according to the needs and circumstances of their environment. In work presented in 2013, Bureš and collaborators described an ensemble-based component system that provided a framework for reasoning about these changing relationships (Bureš et al., 2013). An ensemble differs from an ordinary permanent module arrangement because membership can vary as context and requirements change. This creates engineering difficulties involving coordination, the continuity of responsibilities and the preservation of system properties when the architecture itself is evolving. The research connected component engineering with self-adaptive systems and the design of software that operates under uncertainty, including possible applications in smart infrastructure. Subsequent work addressed how such systems might be verified rather than assuming that dynamically assembled components would automatically remain correct. The Czech contribution is particularly significant for demonstrating that software architecture can be understood as a dynamic process governed by explicit rules instead of a static diagram frozen at deployment. DEECo should consequently be understood as a research framework for investigating dependable adaptation, not as evidence that all Czech industrial systems adopted a common autonomous-component architecture.

Formal verification constitutes a second major field in which Czech researchers have produced identifiable software-engineering results since independence. Testing executes selected inputs and scenarios, whereas formal verification attempts to establish whether a specified property holds across a mathematically defined range of behaviours. The difference becomes important

in concurrent programs, where unusual scheduling sequences may produce failures that ordinary test cases rarely encounter. Model checking represents a system through states and transitions and investigates whether certain undesirable states or temporal patterns are reachable. The technique faces a fundamental scalability obstacle because even comparatively small programs can generate enormous numbers of possible execution states. Researchers must therefore develop strategies for symbolic representation, state-space reduction, parallel exploration and the interpretation of counterexamples. In the Czech Republic, this work became associated particularly with teams at Masaryk University in Brno and with their long-running development of the DiVinE verification tools. The central engineering question was not simply how to prove an abstract property but how to make verification useful for realistic software structures, particularly concurrent applications. This focus connected theoretical reasoning to executable tools and helped distinguish the national contribution from general advances in formal methods made internationally.

The development of DiVinE shows how software verification can itself become a substantial systems-engineering undertaking. Jiří Barnat, Luboš Brim, Milan Češka and Petr Ročkai described DiVinE as a parallel distributed model checker in a 2010 publication associated with Masaryk University's Faculty of Informatics. The project addressed large verification tasks by using several processing resources to explore relevant portions of a system's behaviour. Distributed analysis requires careful coordination because separate workers must avoid uncontrolled duplication while preserving the correctness of the global verification procedure. The implementation of such algorithms therefore confronts practical questions of load balancing, communication overhead, state representation and memory consumption. From a software-engineering perspective, the resulting tool is important because it transforms an abstract specification of correctness into an analysis process that can expose defects in concrete systems. The project also shows that verifying software depends upon the reliable construction of the verification software itself, including reproducible results and clearly defined assumptions. Not every program can be analysed exhaustively within reasonable resources, and the practical usefulness of a verification system depends partly upon recognising this limitation. The relevant Czech achievement lies in original techniques and sustained implementation for large-scale model checking, rather than an assertion that automated verification can replace all traditional testing. As DiVinE evolved, these foundations supported deeper engagement with programming-language semantics and the verification of real C and C++ applications.

The adaptation of model checking to ordinary programming languages became especially important as verification moved beyond models constructed specifically for formal analysis. C and C++ programs interact with operating-system services, manipulate memory directly and rely upon language features whose runtime behaviour may be difficult to reconstruct precisely. Research associated with Petr Ročkai, Vladimír Štill, Ivana Černá and Jiří Barnat developed a virtual-machine architecture intended to make these challenges more tractable. Their 2017 work on DiVM introduced a verification backend with graph-organised memory and an instruction interface based on Low Level Virtual Machine intermediate representation (LLVM IR). This approach allowed system-level functionality to be represented within the verification environment while preserving the possibility of analysing substantial parts of ordinary programs.

Graph-based memory is especially relevant when pointer relationships and object identities change during execution and when the same logical state may have different concrete memory layouts. A sufficiently precise operating environment is equally necessary because analysis can produce misleading results if essential library behaviour or system calls are replaced by unrealistic assumptions. The work demonstrates how compiler representations, memory modelling and operating-system semantics can be combined to support software verification. Its achievement should be understood in terms of improved verification architecture and demonstrable tool behaviour, rather than a claim that all C and C++ programs have become automatically provable.

Brno's research also addressed the difficult problem of checking dynamically allocated structures through static analysis of programs that manipulate pointers. Linked lists, trees and other heap-based organisations can change shape while a program executes, making it impossible to analyse every concrete memory configuration separately. An analysis that reasons only about individual variables may miss errors involving aliasing, invalid references or improper updates to a complex data structure. Kamil Dudka, Petr Peringer and Tomáš Vojnar developed Predator as a practical analyser based on separation logic, with an initial tool publication appearing in 2011. Separation logic provides a formal language for describing portions of memory and the relationships between them, including circumstances in which distinct components operate on separate regions. The Predator research was subsequently extended to deal with lower-level memory operations and more demanding representations of pointer-based structures. Such extensions are technically significant because industrial C software relies upon memory operations that can violate simplifying assumptions made by elegant theoretical analyses. The resulting work joined abstract interpretation, symbolic memory graphs and careful implementation of program-analysis algorithms. Its Czech institutional setting included Brno University of Technology and, in later collaborations, engineers associated with Red Hat's Czech operations. The importance of Predator lies in a reproducible research programme for analysing real memory-safety problems, with stated boundaries concerning the program classes and properties that the tool can handle.

Automated program analysis developed further through the Symbiotic project, which combined several techniques rather than treating any single method as a universal solution. Static slicing can remove statements irrelevant to a particular property, thereby reducing the material that a verifier must examine. Symbolic execution represents classes of possible inputs through logical constraints and explores the paths arising from alternative execution choices. Instrumentation introduces checks that make certain violations observable within the analysed program, while induction can support reasoning about behaviours that involve repeated execution. The Symbiotic 8 publication by Marek Chalupa and colleagues described an integration of these approaches, including an extension that combined symbolic execution with induction for analysing programs containing potentially unbounded loops. The researchers also incorporated and adapted other analysis components, demonstrating how an engineering tool can gain value from combining specialised algorithms within a coherent processing pipeline. The project involved Masaryk University and Brno University of Technology, reflecting cooperation across local institutions rather than the work of an isolated laboratory. Its technical meaning is best

understood through the distinct errors detected and properties proved, not through a simplified ranking of the number of warnings produced. Symbiotic exemplifies the transition from theoretical verification procedures towards programmable toolchains intended to supplement practical software-quality assurance.

The interaction of static analysis, model checking and testing exposes an important methodological principle that remained relevant throughout the period under review. A unit test confirms observed behaviour for specified inputs, whereas static analysis attempts to infer properties without executing every concrete input combination. Model checking can provide exhaustive evidence within a chosen formal model, but the reliability of that evidence depends on whether the model adequately represents the running program. A false alarm may arise when an abstraction admits behaviours that cannot occur, while a missed defect can result from incomplete modelling or unsupported language features. Soundness, completeness, precision and scalability therefore express different properties of an analysis method and must not be conflated. Czech work on DiVinE, Predator and Symbiotic illustrates the practical significance of this distinction because the tools address different classes of programs and defects. Their results are often assessed in international evaluation settings, but a benchmark position alone cannot establish that a tool is suitable for every industrial application. Researchers must examine the property checked, the assumptions made, the time and memory required and the quality of diagnostic evidence returned to developers. This more discriminating perspective helps explain why mature software engineering uses combinations of tests, reviews, formal analysis and operational monitoring. The long-term contribution of Czech verification research is consequently methodological as well as technological, making reliability questions more explicit and supplying tools with which some of those questions can be investigated.

Programming languages shape software quality because they determine which errors can be prevented syntactically, detected during compilation or left to the execution environment. The expansion of Java and later managed-language ecosystems in the Czech Republic transformed the relationship between professional programming and concerns such as memory management, portability and modularity. Language facilities for type checking, interface definition and exception handling made some software structures easier to reason about, although they could not eliminate errors in application logic. Researchers in Prague and Brno investigated software systems built with such languages while also developing tools that made language features more accessible to programmers. The international company JetBrains, founded in Prague in 2000, provides a distinctive example of developer-tool innovation with a strong Czech organisational connection rather than an exclusively Czech research lineage. Its IntelliJ IDEA environment, introduced in 2001, advanced interactive code navigation, refactoring and inspection in the Java development ecosystem. JetBrains subsequently developed further development environments and the Kotlin programming language, linking language design with the requirements of professional tools. It would be inaccurate to describe all these products as the work of a nationally homogeneous Czech team, because the company's engineering activity and intellectual contributions have been international. Their relevance to the present study lies in demonstrating how an enterprise historically based in Prague could help shape widely used practices of code creation and maintenance.

Refactoring became an especially influential part of professional programming because existing code often needs structural improvement without a change in its observable behaviour. Moving a method, renaming a symbol or extracting a shared component may appear simple until references extend across many files and dependencies. An automated refactoring tool must understand language syntax, name resolution and relationships between program elements well enough to avoid breaking those dependencies. IntelliJ IDEA contributed to the popularisation of refactoring and inspection facilities through a development interface intended to turn complex transformations into routine programmer operations. JetBrains documented advanced navigation and refactoring in the product's early history and later made an open-source Community Edition available in 2009. The coexistence of commercial and open components created opportunities for community inspection, extension and integration, while continuing to rely on substantial professional maintenance. NetBeans had earlier followed a different organisational trajectory, but both examples show why programming environments can be more intellectually consequential than the applications created in them. Their importance should not be measured only through market share, because an interface concept may influence competing products and become part of common engineering expectations. At the same time, a convenient refactoring command is not a mathematical guarantee, and robust development still requires compilation, regression tests and review of intended behaviour. The lesson of these tools is that software-engineering innovation often appears as a disciplined reduction in the cost and risk of making necessary changes.

Compiler research and development provide a complementary perspective on the relationship between programming-language foundations and executable software. A compiler must preserve the intended meaning of a program while translating it into a representation suitable for a target architecture or execution environment. Optimisation complicates this task because transformations can affect control flow, data dependencies, timing and the reproducibility of the resulting build. Researchers associated with Charles University, including Jan Hubička, have contributed to investigations of compiler performance and the parallel execution of compilation tasks. A 2022 study conducted with collaborators examined parallel compilation in the GNU Compiler Collection (GCC) and reported improvements through adjustments involving link-time optimisation. The significance of such work is not simply that a compiler runs faster, but that productivity improvements must remain compatible with constraints on code correctness and reproducible builds. Open compiler infrastructure creates opportunities for contributions from researchers working in smaller national systems, even when the project is governed through an international community. The Czech case thus illustrates how expertise developed within universities and industrial engineering teams can inform a software tool used far beyond the country. It also cautions against attributing an entire global compiler project to a national research group simply because individual contributors possess Czech affiliations.

Software testing evolved from a final activity conducted after implementation towards an iterative part of the development process. Unit tests examine small sections of functionality, integration tests investigate relationships among components and system tests explore behaviour under more realistic combinations of services and inputs. Regression tests are particularly important for mature products because a correction in one part of the code may inadvertently reintroduce

an earlier defect elsewhere. Automated tests make rapid feedback possible, but their existence does not guarantee that the right properties have been checked or that representative inputs have been selected. The development of substantial Czech-based software companies increased the practical demand for systematic defect management and reproducible validation across successive product releases. Research on formal analysis provided an additional perspective by investigating behaviours that ordinary example-based tests were unlikely to expose. Symbiotic, for instance, linked symbolic reasoning to safety checking, while DiVinE focused on formally represented behaviours involving potentially complex execution paths. Such tools are complementary rather than interchangeable because they use different abstractions, expose different failures and require distinct forms of interpretation. A scientifically responsible account should therefore evaluate testing innovations through demonstrated coverage, defect detection, diagnostic quality and the costs imposed upon development. The growing integration of tests into ordinary engineering work was an important cultural change, but it cannot be reduced to the adoption of a particular commercially successful test framework.

The expansion of continuous integration transformed software development by making building and checking code a recurring activity rather than an exceptional pre-release event. A shared repository records the sequence of changes, while an automated integration process can compile proposed revisions, execute tests and report results before release. When these activities are organised carefully, developers can discover incompatibilities close to the change that introduced them rather than months later. JetBrains developed TeamCity as a continuous integration and deployment product during the period in which its portfolio of professional developer tools expanded internationally. The engineering value of such systems depends on build reproducibility, trustworthy configuration, dependency control and the ability to diagnose failures, not merely the appearance of a successful status indicator. Automated delivery must therefore preserve human judgement about acceptance criteria, security, backward compatibility and the consequences of deployment. In Czech companies and research groups, the adoption of internationally recognised integration practices accompanied greater participation in projects maintained by teams distributed across several countries. The contribution of Prague-based development-tool enterprises must be considered alongside the influence of open-source tools and international software engineering standards. Continuous integration ultimately changed the temporal organisation of quality assurance by making evidence about the current state of a codebase available throughout its development.

Open-source engineering became especially prominent in Brno following the expansion of international technology enterprises cooperating with local specialists and universities. CzechInvest reported in January 2007 that Red Hat had established a software-development centre in Brno, explicitly linking the investment to the available regional pool of technical expertise. Participation in projects associated with Linux and related open technologies exposed developers to source review, public issue tracking and distributed decision-making across organisational boundaries. Such work differs from ordinary outsourcing because engineers may contribute directly to the shared codebase and participate in technical discussions conducted within a global project. Open-source governance nevertheless varies, and publishing source code is not sufficient to guarantee openness in project direction, compatibility or long-term

maintenance. Successful contributions require tests, documentation, reviewable patches and careful consideration of how modifications affect existing users. The region's universities supplied essential education and research capacity, while professional development teams provided an environment in which specialised programming skills could be exercised on production software. Collaborations involving verification researchers and industrial engineers, including later work related to Predator, demonstrate the potential for exchanging expertise across these institutional settings. The result was not an isolated Czech branch of the open-source world but a locally concentrated participation in internationally organised engineering communities. This experience helped broaden the understanding of software innovation from company-owned products towards technical contributions whose benefits may be shared through open licences.

The reliability of software also depends upon its performance under workloads that differ from the conditions encountered during initial development. An application may compute the correct answer but fail to provide it within a useful time, or it may consume more memory than is available in its intended operating environment. Performance engineering therefore investigates latency, throughput, resource usage and their relationship to program structure, compiler behaviour and concurrent execution. Researchers connected with Charles University's Department of Distributed and Dependable Systems developed approaches to dynamic program analysis, including work on reusable instrumentation for the Java Virtual Machine (JVM). Ansaloni and collaborators described methods for modularity and reuse in JVM analysis tools, addressing a practical obstacle to constructing sophisticated monitoring and experimentation systems. Such work matters because understanding performance requires reliable measurement rather than impressions derived from a limited demonstration. Instrumentation itself can alter execution characteristics, so experimental design must consider whether observation introduces distortions that affect the conclusions. Reproducible workloads, appropriate baselines and statistical treatment of variation are indispensable when comparing competing implementations or optimisation strategies. These studies demonstrate that software-performance research belongs to engineering methodology and not merely to the purchase of faster computing equipment.

The development of distributed applications expanded the software architect's responsibilities beyond the internal correctness of individual programs. A service may function perfectly when executed in isolation yet behave incorrectly when communication is delayed, another service is unavailable or several components update related information concurrently. The growing use of service-oriented and later microservice architectures increased the importance of explicit interfaces, failure handling and systematic compatibility management. These issues were relevant to Czech software enterprises, research infrastructures and university laboratories participating in complex international software projects. The Prague component-engineering tradition offered a conceptual language for analysing such arrangements through defined contracts, deployment descriptions and expectations about component interaction. However, a microservice is not identical to a SOFA component, and the history of component models should not be presented as though it directly caused the emergence of all later distributed architectures. The more defensible interpretation is that both traditions address a shared need to control

complexity through abstraction and carefully specified relationships. A dependable architecture must also confront consistency, fault isolation, monitoring and the operational consequences of upgrading part of a running system. Modern cloud platforms can automate provisioning and deployment, but they do not remove the developer's responsibility for specifying behaviour when dependencies fail. This distinction is central to evaluating how Czech software-engineering research interacted with the growing technological sophistication of practical information systems.

The value of formal engineering methods becomes particularly evident in systems where a rare software defect may produce serious economic or operational consequences. Medical devices, industrial controls, transport management systems and scientific instruments differ in their immediate functions, yet all can demand evidence that critical software behaves within specified limits. Producing such evidence requires requirements that identify hazards and unacceptable states before test plans and verification conditions can be defined. The Prague work on behaviour protocols provides methods for examining interaction assumptions, while Brno's verification tools offer complementary techniques for reasoning about program execution. The verification of ensemble-based component systems brought these perspectives closer together by examining dynamic assemblies through explicit models of their behaviour. The existence of a published verifier does not automatically certify a deployed product, since assurance also depends upon the precise property checked and the correspondence between model and implementation. Industrial adoption requires additional processes for traceability, configuration management, review and the documentation of unresolved limitations. Scientific research can nevertheless improve these processes by developing more expressive specifications, better diagnostic algorithms and clearer relationships between abstract properties and executable behaviour. The distinctive contribution of Czech research is therefore visible in the methods available for constructing dependable systems, even when the applications that use such methods belong to internationally regulated sectors.

Maintenance became a defining challenge of mature Czech software projects because successful applications often survive far longer than their original developers anticipated. Over time, code can accumulate duplicated logic, outdated dependencies, inconsistent interfaces and assumptions that no longer correspond to current requirements. Technical debt describes certain future costs arising when expedient development choices make subsequent modification more difficult, but the term should not be used as a universal label for old code. Some established software structures remain dependable precisely because they have been exercised and corrected over many years. Software engineering therefore needs evidence about change frequency, defect patterns, architectural coupling and the costs of implementing new functionality. Modern programming environments help developers understand these relationships through navigation, inspections, dependency analysis and controlled refactoring. Research on behavioural specifications adds another perspective by asking whether changes preserve permitted interaction sequences rather than merely retaining compilable method signatures. The long history of the NetBeans platform illustrates the organisational challenges of preserving a large codebase through changing owners, programming standards and contributor communities. In 2019, NetBeans became an Apache Software Foundation top-level project,

formalising a governance model intended to sustain continued development through open participation. The wider historical lesson is that maintainability depends on architectural judgement, shared knowledge and institutional continuity as much as on the functionality available in any single release.

Open-source projects made the connection between local expertise and international software governance especially visible during the final decades of the study. A programmer working in Brno or Prague might contribute to a repository maintained by specialists on several continents while remaining accountable to the same review procedures as other participants. This arrangement can improve access to sophisticated engineering problems, but it also places demands on communication, documentation and the ability to explain implementation choices publicly. The NetBeans transition to Apache provides one example of governance becoming a central feature of the project's identity rather than a secondary administrative matter. The Apache Software Foundation announced the platform's graduation in April 2019 after a period in its incubator, reflecting the completion of community and organisational requirements. The Red Hat development presence in Brno illustrates a different configuration, in which an international company employed local engineers to participate in open technical ecosystems. These organisational models should not be conflated, because foundation-led governance, company sponsorship and individual voluntary contribution distribute authority in different ways. The ability to sustain reliable software across such arrangements depends upon transparent interfaces, release procedures, source provenance and attention to the rights associated with third-party code. Open-source participation consequently contributed to professionalisation by making code quality subject to scrutiny outside the immediate employer or original project team.

University education was fundamental to the reproduction of Czech software-engineering expertise throughout the three decades under consideration. Charles University provided a research environment connecting software architecture, programming-language methods and the investigation of dependable distributed systems. Masaryk University’s Faculty of Informatics cultivated formal analysis and software verification in close contact with computer science education and research projects. Brno University of Technology contributed additional expertise in programming, static analysis and practical engineering of verification tools. The experience of NetBeans demonstrates how student development can become a significant professional undertaking when institutional mentoring, technical ability and entrepreneurial initiative converge. These examples nevertheless do not imply that every graduate became an academic researcher or that every local employer carried out original software-engineering research. Universities serve several complementary functions, including the transmission of programming fundamentals, the preparation of researchers and the formation of a labour force capable of working with rapidly evolving technologies. International conferences, shared source repositories and collaborative research grants increasingly gave students access to methods developed beyond the national system. The sustainability of national expertise also depended upon doctoral supervision, technical career prospects and the possibility of moving between academic laboratories and professional development organisations. A credible history of Czech software engineering must therefore connect publications and tools to the educational structures that enabled successive generations to extend them.

Secure software construction intersects with cybersecurity while retaining a distinct engineering identity focused on how applications are produced and maintained. Developers need to evaluate input validation, access controls, error handling and external libraries as properties of their implementation rather than as concerns delegated entirely to network administrators. The growing complexity of software supply chains made dependency management and reproducible builds important prerequisites for trustworthy releases. A programme can pass functional tests and still contain vulnerable dependencies or assumptions about its execution environment that create opportunities for misuse. Static analysers, code review and automated build systems can identify some of these weaknesses, but they differ in what they inspect and how much confidence they provide. Research such as Predator contributes techniques for analysing low-level memory operations, whereas a broader secure-development process must address many additional sources of risk. The Czech experience illustrates the institutional proximity of software engineering and cybersecurity, particularly in Brno, without requiring that their research agendas be treated as identical. Formal verification of selected safety properties can provide strong evidence within a defined scope, but it does not establish universal security against every future threat. Professional software practice therefore demands layered assurance, transparent assumptions and continuous attention to changes in dependencies, operational conditions and attack techniques.

By the early 2020s, artificial intelligence began changing the everyday instruments used to design, write and review software. Language-model-based assistants could suggest code fragments, translate descriptions into candidate implementations and help programmers navigate unfamiliar libraries or programming languages. These capabilities extended earlier traditions of code completion and automated refactoring but introduced an important difference because the suggestions were generated probabilistically rather than derived solely from explicit language rules. International studies reported benefits in some programming workflows while also documenting inconsistent behaviour and concerns about the correctness and security of generated code. A 2025 study of professional attitudes towards coding assistants, e.g., examined how programmers used these systems across implementation, testing, defect analysis and refactoring tasks. Research published before the end of 2025 also demonstrated that generated code requires independent security review rather than unquestioning adoption. For Czech universities and companies, such developments presented opportunities to experiment with new development methods, but participation should not be mistaken for evidence of a uniquely Czech invention. The earlier national strengths in formal methods, software architecture and programming tools provided relevant intellectual resources for assessing whether generated software meets explicit requirements. The resulting question is not whether machine assistance eliminates programming expertise, but how human judgement, automated generation and rigorous verification can be organised responsibly. The development of intelligent tools therefore reinforced the long-standing software-engineering problem of distinguishing a plausible implementation from one supported by adequate evidence of correctness.

Assessing national achievement in software engineering requires a broader set of criteria than the number of locally registered software companies or the popularity of individual applications. Scientific originality can be demonstrated through identifiable algorithms, formal models,

rigorous analyses, published methods and independently evaluated research tools. Engineering achievement may instead consist in constructing a robust development environment, supporting a complex codebase or making a substantial contribution to international software infrastructure. Commercial achievement should be analysed through product adoption and organisational outcomes, while recognising that customers cannot normally inspect all of the research and development processes behind a product. The cases of SOFA, DEECo, DiVinE, Predator and Symbiotic are therefore historically distinct from the commercial trajectories of NetBeans, IntelliJ IDEA and TeamCity. Their common ground is the attempt to improve how software is created, understood and changed, but each makes a different claim to technical and scientific significance. Attribution also requires attention to institutional affiliation, international authorship, employer location and the date at which particular work was undertaken. A publication by a Czech researcher working abroad is not automatically evidence of a discovery produced by a Czech institution, just as a local office of a multinational enterprise does not make its entire global product portfolio a national invention. These distinctions protect the historical argument against exaggeration while allowing legitimate contributions by internationally connected Czech research communities to be recognised.

Between 1993 and 2025, Czech software engineering evolved through a cumulative interaction of academic inquiry, engineering practice, commercial development and participation in global software communities. The transition from inherited programming expertise to a diverse professional ecosystem created space for student initiatives, specialised companies and internationally competitive research groups. NetBeans demonstrated the potential of locally initiated developer tools to acquire global significance, while the Prague-based activities of JetBrains showed how professional programming environments could become an internationally visible product specialisation. Research at Charles University contributed methods for describing and assembling components whose behaviour must remain coherent under changing architectural conditions. Work at Masaryk University and Brno University of Technology advanced practical verification and static analysis through tools that linked rigorous reasoning with ordinary programming languages. Open-source development and cooperation with international technology enterprises expanded the settings in which these skills could be used and evaluated. The transition towards automated integration, deeper software analysis and intelligent code assistance transformed working methods without removing the need for precise requirements and competent human judgement. Important challenges remained by 2025, including scalable verification, long-term maintainability, supply-chain reliability and the interpretation of software generated by probabilistic systems. The central historical achievement was therefore neither a single invention nor a simple increase in code production, but the development of research and engineering capabilities able to address the growing complexity of contemporary software. In this sense, Czech experience illustrates how sustained scientific specialisation can complement practical technological entrepreneurship within an increasingly integrated European and global digital environment.

Computer Vision, Image Processing, Computer Graphics and Human–Computer Interaction

The development of computer vision and computer graphics in the Czech Republic between 1993 and 2025 illustrates how mathematical research became a practical instrument for interpreting and constructing visual worlds. Computer vision attempts to infer objects, geometry, motion and meaning from measured images, whereas computer graphics generates images from mathematical or digital scene descriptions. Image processing supplies transformations and measurements essential to both fields, including enhancement, registration, segmentation and estimation of uncertainty. Human–computer interaction adds a different question concerning how people perceive, control and evaluate systems built upon these techniques. The boundaries are increasingly permeable because three-dimensional reconstruction may support graphics, while synthetic imagery can assist computer-vision training. Czech development therefore cannot be represented accurately by a single sequence of cameras, display devices or commercial software releases. Its intellectual history also involves geometry, optimisation, perception, experimental methodology and the social consequences of automated interpretation. An account of national achievements must identify where original algorithms were developed and how their validity was demonstrated. Throughout this chapter, internationally collaborative work is distinguished from research undertaken within Czech institutions, without denying their productive relationship.

The independent republic inherited substantial traditions in cybernetics, applied mathematics, optics, image analysis and technical visualisation from Czechoslovak higher education and research institutes. Earlier work provided expertise in signal processing, geometric measurement, pattern recognition and the automation of industrial inspection. The political changes after 1989 broadened access to international conferences, specialist journals, computing hardware and experimental collaborations. When the Czech Republic was established in 1993, university departments did not need to invent visual computing as an entirely new discipline. Their immediate challenge was to develop existing mathematical competence within new research funding and international publication environments. Improvements in workstations and digital cameras made previously expensive experiments increasingly accessible to university groups and smaller laboratories. The appearance of digital imaging equipment also connected theoretical questions to manufacturing, transport, medicine and cultural documentation. Fundamental work nevertheless remained necessary because faster hardware could not solve problems of ambiguous correspondences or incomplete observations by itself. The transformation consequently concerned research culture and methods of evaluation as much as the diffusion of new imaging technology. It created conditions in which specialised Czech schools could contribute identifiable results to worldwide visual computing.

Prague became an important centre of this development through the Czech Technical University and its combination of cybernetics, computer graphics and applied mathematics. The Center for Machine Perception was established within the university's Department of Cybernetics in 1996, creating a more concentrated environment for visual research. Its documented activities encompassed scene reconstruction, stereo correspondence, camera geometry, visual

recognition, tracking and biomedical image analysis. These topics shared the demand to extract stable conclusions from images whose appearance changes with lighting, viewpoint and movement. Research groups led by figures including Jiří Matas, Tomáš Pajdla and Radim Šára approached different parts of that problem through complementary methods. The institutional setting also enabled doctoral researchers to work on theoretical questions while collaborating with foreign laboratories. Such continuity across research projects helped experimental knowledge accumulate rather than disappearing when individual software demonstrations ended. The Centre's significance therefore lies not merely in the number of its publications but in its sustained formulation of reusable computational problems. An institutional report published in 2004 provides contemporary evidence of this broad research profile.

A particularly influential contribution came from the work of Jiří Matas, Ondřej Chum, Martin Urban and Tomáš Pajdla on maximally stable extremal regions. Their 2004 article addressed wide-baseline stereo, where the same scene is photographed from substantially different camera positions. Instead of assuming that corresponding objects preserve identical pixel neighbourhoods, the method identifies stable connected regions across variations in image intensity. The resulting image elements provide comparatively robust candidates for correspondence under changes of viewpoint and illumination. Their value rested both on a mathematical account of stability and on an efficient procedure for detecting candidate regions. The original work included experimental matching results rather than relying solely on theoretical reasoning. This distinction matters because feature detectors become genuinely useful only when integrated into broader geometric estimation procedures. The contribution illustrates how a carefully defined image primitive can have an extended methodological life across subsequent technological generations.

Reliable feature matching also requires methods capable of rejecting incorrect correspondences in the presence of substantial visual noise. Random sample consensus, widely known as RANSAC (Random Sample Consensus), became a central strategy for estimating geometric models from observations containing many outliers. Czech researchers did not originate the general RANSAC concept, but Ondřej Chum and Jiří Matas developed influential improvements to its computational use. Their research examined the randomisation of verification and the trade-off between hypothesis testing and computational expenditure. Efficient estimation matters because an otherwise accurate geometric algorithm may be impractical when many images must be processed. A method that rejects unsuitable hypotheses earlier can make larger retrieval and reconstruction systems more responsive. The importance of such advances is methodological rather than dependent upon one type of camera or industrial product. They strengthen the credibility of visual inference when observations are uncertain and geometric relationships must be established from incomplete evidence. Prague's work on robust estimation accordingly offers an example of scientific innovation within a mature international algorithmic tradition. Its relevance extends to visual localisation, panorama construction, photogrammetry and robot perception.

As digital photography and networked image collections grew, visual recognition increasingly became a question of finding relevant instances inside very large databases. This problem differs from simple image classification because a search system must distinguish a particular building,

object or scene from thousands of visually similar alternatives. Researchers investigated local feature vocabularies, geometric verification and methods for recovering items missed by an initial query. Ondřej Chum contributed to research on automatic query expansion during an international collaboration based at Oxford. That work used initial retrieval results to obtain a richer representation of the queried object and improve recall in large image collections. Its multinational authorship is essential to the historical attribution, even though Chum's scholarly trajectory was connected with the Czech vision community. Search accuracy could not be judged merely by the attractiveness of returned images because false matches and omissions both affected scientific usefulness. Retrieval methods subsequently acquired significance for visual archives, landmark recognition and the organisation of large multimedia datasets. Czech scholarship thus participated in a wider transition from isolated image interpretation towards searchable collections of visual knowledge.

Matching across markedly different viewpoints remained a difficult problem even after local image descriptors became standard tools. A tilted camera can transform shapes so strongly that ordinary interest-point matching produces too few trustworthy correspondences. Dmytro Mishkin, Jiří Matas and Michal Perďoch addressed this difficulty through matching on demand with view synthesis, known as MODS. Their approach progressively introduced more demanding feature detection and synthetic views when simpler matching attempts did not provide reliable geometry. The system therefore balanced computational expense against the observed difficulty of the image pair. This adaptive principle is important because uniformly applying the costliest procedure wastes resources on ordinary cases. Experimental evaluation demonstrated the method's usefulness for challenging wide-baseline problems rather than merely proposing an architectural idea. Such work connects robust visual matching with practical image registration and geometric reconstruction. It also demonstrates that carefully designed classical pipelines remained competitive despite the accelerating development of neural computer vision. Historical accounts should recognise these parallel methodological trajectories rather than treating learning-based systems as the complete replacement of earlier vision research.

Three-dimensional reconstruction provides another distinctive area of Czech theoretical expertise because photographs reveal only projections of spatial structure. Estimating the original arrangement of cameras and objects requires mathematical assumptions concerning perspective, calibration and relationships among image points. Tomáš Pajdla and collaborating researchers investigated camera geometry, non-standard imaging devices and reconstruction from multiple views. Their work linked projective geometry with algorithms capable of recovering relative positions despite sparse or imperfect correspondences. Such problems may appear abstract, yet reconstruction depends on numerical procedures that remain stable with limited observations. The field also demonstrates the difference between geometrically plausible visualisations and quantitatively trustworthy measurements of space. A reconstructed scene can appear convincing while still containing serious scale or calibration errors. Research therefore examined algebraic constraints, uncertainty and the structure of solvable camera configurations. These questions supported applications ranging from architectural documentation and robotics to autonomous localisation and scientific measurement.

A more specialised contribution to geometric reconstruction concerned the automatic solution of minimal estimation problems. Minimal solvers determine camera or scene parameters from the smallest suitable collection of measurements allowed by the model. Zuzana Kukelová, Martin Bujňák and Tomáš Pajdla proposed an automatic generator of such solvers in 2008. Their method transformed systems of polynomial equations into executable numerical procedures, reducing dependence on laborious problem-specific derivations. Subsequent work developed polynomial eigenvalue approaches for further classes of minimal computer-vision problems. These results are significant because the mathematical structure of the problem directly determines the reliability of practical pose estimation. Automated generation made specialised geometric computation more accessible to researchers concerned primarily with imaging applications. At the same time, automatically obtained solutions still required verification of numerical conditioning and sensitivity to observations. The research illustrates how original work in algebraic computation can become a foundational tool within experimental visual systems. It also reveals the sustained importance of mathematical theory beneath increasingly sophisticated image-based products.

Stereoscopic vision reconstructs depth from correspondence between two or more images, but its apparent simplicity conceals substantial statistical difficulty. Repeating textures, reflective surfaces and hidden regions can produce multiple plausible candidates for the same physical location. Work associated with Radim Šára and Jan Čech explored strategies for selecting, evaluating and propagating correspondences under such uncertainty. In later projects, Čech examined fast scene flow and correspondence methods designed to recover changes in three-dimensional structure over time. These questions differ from static image matching because motion and temporal consistency introduce additional geometric constraints. A reliable system must separate genuine movement from apparent displacement caused by camera motion or incorrect matches. Efficiency also becomes more demanding when many video frames must be analysed without delaying a robotic or interactive application. The Czech contribution lies in systematic attention to correspondence quality and geometric interpretation rather than in any single display technology. Its results helped connect the country's classical vision expertise with the growing international study of dynamic scenes.

Tracking objects through video adds the difficult requirement of preserving identity while their appearance and visibility change. A target may temporarily disappear behind another object or move outside the camera's field before returning. Visual tracking therefore combines representation of appearance with motion estimates and explicit decisions about uncertainty. The Prague visual-recognition community developed research on long-term tracking, object detection and the recovery of targets after failure. Jiří Matas and colleagues approached these questions as continuing problems of experimental recognition rather than simple applications of general classification software. Their research environment made it possible to compare tracking methods under demanding sequences containing occlusion, viewpoint change and deformation. Video tracking also provided a practical connection with sports analysis, traffic monitoring and robotics. Its scientific difficulty derives partly from the absence of a reliable independent measurement of object identity in every frame. Evaluation protocols must therefore address sustained accuracy, recovery after failure and the consequences of false detections. This

combination of algorithm design and systematic benchmarking remains central to trustworthy analysis of moving imagery.

The spread of deep neural networks during the 2010s transformed the tools available for recognising objects, segmenting images and estimating visual geometry. Learned models increasingly replaced manually designed feature representations in tasks supported by sufficiently large training datasets. Czech research groups adapted by combining established geometric knowledge with new approaches to statistical representation learning. A crucial question concerned whether a network could generalise to unfamiliar lighting, weather, camera configurations and object categories. Improvements on a popular benchmark were not automatically equivalent to robustness in industrial or medical environments. Research also investigated the relative merits of learned matching and carefully optimised classical approaches. A multinational benchmarking study involving Jiří Matas and colleagues analysed how matching accuracy depended on the complete reconstruction pipeline. This work cautioned against judging features in isolation from the geometric estimators that consume them. Such findings helped preserve methodological continuity between classical geometry and modern machine learning.

Beyond Prague, Brno developed a substantial profile in image processing, machine vision and the technological integration of visual sensing. Brno University of Technology combined technical education with research into recognition, video processing and image-based industrial systems. Pavel Zemčík contributed to this broader research environment through projects involving multimedia data, cameras and embedded visual technologies. Other groups investigated manufacturing inspection, anomaly detection and methods for observing traffic or industrial processes. Their work illustrates a different but complementary orientation from the mathematically concentrated geometry research undertaken in Prague. Industrial cameras often operate under constraints involving limited illumination, narrow processing time and the need to identify rare defects. Algorithms must therefore be designed around the characteristics of production environments rather than evaluated only on generic photographic collections. Reliable visual inspection may combine optical engineering, controlled acquisition, pattern recognition and statistical decisions about acceptable uncertainty.

The movement of image processing towards embedded devices created further research questions about computational efficiency and system reliability. Visual data arriving continuously from a camera cannot always be transferred to a distant server without unacceptable delay. Local processing may instead perform feature extraction, object detection or preliminary filtering directly on specialised hardware. Such arrangements require choices concerning processor architecture, memory consumption, energy use and communication bandwidth. In transport applications, detection errors can affect human safety and demand more rigorous testing than ordinary consumer photography. Industrial applications similarly require systems that remain dependable across changing equipment, materials and illumination conditions. Czech research combining hardware-oriented engineering with visual algorithms addressed practical aspects of these constraints. Its significance lies in translating computational principles into functioning measurement environments, not in assuming that every integration is an original scientific discovery. The gradual adoption of learned models

created new opportunities but also raised challenges concerning maintainability and the interpretation of errors. Embedded vision therefore demonstrates why technological progress must be assessed through reliability and operational context as well as recognition accuracy.

Biomedical image analysis formed an especially productive intersection of Czech computer vision, numerical mathematics and experimental science. Medical images may reveal anatomy or disease indirectly, through measurements whose meaning depends on acquisition settings and tissue properties. A useful algorithm consequently needs a mathematically justified relation between recorded intensity and the biological question being examined. Jan Kybic developed influential methods for image registration, segmentation and the estimation of registration uncertainty. Registration determines how corresponding structures in different images can be aligned despite movement, distortion or anatomical variation. Kybic's collaboration with Michael Unser produced a parametric elastic registration method using mathematical deformation models. Such methods can compare images collected at different times and support the interpretation of clinical or experimental change. Their contribution concerns the reliability of computational alignment rather than a claim to diagnose disease independently. The biomedical field thereby illustrates how foundational image algorithms can acquire substantial practical importance without abandoning mathematical rigour.

Digital histopathology provides another demanding environment because slides may be exceptionally large and tissue appearance changes with staining procedures. Microscopic features that are valuable to a pathologist can also resemble artefacts introduced during specimen preparation or scanning. Image alignment, segmentation and classification therefore need to recognise the difference between meaningful tissue structure and acquisition variation. Jiří Borovec, Arrate Muñoz-Barrutia and Jan Kybic benchmarked registration methods for histological sections prepared with different stains. Their study compared methods on a substantial collection of paired images and examined accuracy, robustness and computational effort. The methodological achievement lay partly in creating conditions for more reliable comparative evaluation of registration strategies. Subsequent biomedical work involving Kybic and colleagues also addressed classification and segmentation with limited or imperfect annotations. These problems are particularly relevant where expert labels are costly or where clinically important patterns occupy small image regions.

Research microscopy presents similar obstacles in cell counting, object delineation and the measurement of biological change over time. Cells frequently touch, overlap or vary in shape, making a simple brightness threshold inadequate for reliable segmentation. Time-lapse images introduce additional difficulties because cells move, divide and disappear between successive observations. Segmentation must therefore be distinguished from tracking, which attempts to maintain correspondences between observations of the same biological entities. Czech imaging and computer science laboratories developed approaches that draw upon signal processing, optimisation and machine learning for such tasks. Their work benefits from collaborations with biologists who can specify meaningful validation criteria and provide expert interpretations. Techniques that work well in one microscopy modality may require substantial adaptation when illumination or staining changes. Moreover, improved computation does not remove experimental sources of uncertainty or biological variability. The value of automatic microscopy

analysis is consequently measured by reproducible biological information rather than by the number of visually attractive masks it produces. This example demonstrates how image processing can become a research instrument within another science.

Computer graphics developed along a partly different institutional path because its central problem is the construction of visual representations rather than inference from camera data. The Czech Technical University maintained a Department of Computer Graphics and Interaction, where research included scene representation, realistic image synthesis and virtual environments. Jiří Žára was among the prominent figures associated with the development of this academic environment. Three-dimensional modelling requires methods for representing geometry, materials, light sources and spatial relationships in a computationally manageable form. The resulting systems may be used for architecture, engineering, training and cultural interpretation as well as entertainment. Research in real-time rendering differs from offline image production because interactive applications impose strict limits on the time available for each frame. Czech graphics researchers investigated how to balance visual fidelity with efficiency and controllability. The spread of graphics-processing hardware broadened experimental possibilities while also increasing demands for reproducible methods. This development established a foundation for later intersections with scientific visualisation and virtual or augmented reality.

A particularly important graphics direction was physically based rendering, which attempts to reproduce light propagation using models consistent with optical phenomena. A plausible picture may be obtained through artistic shortcuts, but physically informative synthesis requires attention to reflection, scattering and material properties. At Charles University, the Computer Graphics Group developed research in light transport simulation, appearance modelling and Monte Carlo computational methods. Jaroslav Křivánek was an influential member of that group and contributed to internationally collaborative work on realistic image synthesis. Rendering complex scenes requires estimating vast numbers of possible light paths, only some of which make substantial contributions to the final image. The research challenge is therefore not simply to increase the number of simulated rays but to allocate computation efficiently. Monte Carlo estimators offer flexible tools, yet their noise and convergence characteristics must be understood mathematically. Methods designed for ordinary surfaces may perform poorly when light travels through fog, smoke or other participating media. Czech research addressed these difficulties by combining probability, physical modelling and careful algorithmic experimentation. Its significance lies in methodological contributions that can be transferred between different rendering engines and application environments.

A notable example is the 2014 study that unified points, beams and paths in volumetric light transport simulation. The international research team included Jaroslav Křivánek, Petr Vévoda and Martin Šik from Charles University alongside collaborators from other institutions. Their method combined complementary estimation strategies for scenes containing participating media such as fog or smoke. These environments are challenging because light may scatter repeatedly before reaching a camera or simulated observer. An algorithm effective for one density or scattering regime can become inefficient under different physical conditions. Combining estimation techniques provides a means of treating this variation without committing to only one

computational strategy. The contribution should be evaluated as a new rendering method rather than merely as a demonstration of convincing special effects. It also shows how university research on abstract transport problems can become relevant to film, visualisation and industrial design. The authorship and institutional affiliations further illustrate the collaborative character of internationally significant Czech computer graphics research.

The relationship between academic graphics and software production became visible through the development of the Corona Renderer and its associated Czech research community. Jaroslav Křivánek was involved in establishing Render Legion in 2014, linking research on light transport with a commercial rendering product. The company's later corporate history demonstrates that a successful technology can retain scientific origins while becoming part of a larger international software organisation. Academic work and product engineering nonetheless operate under different forms of evidence and responsibility. A paper must explain a method's originality and limitations, whereas commercial software must also satisfy users' requirements for stability, integration and usability. Industrial deployment may reveal practical problems that were not prominent in controlled research demonstrations. Conversely, access to demanding production scenes can inspire new questions about sampling, noise reduction and predictable image synthesis. The interaction should therefore be analysed as knowledge exchange rather than proof that every software improvement represents a scientific discovery. The Czech example illustrates a plausible pathway from university-based algorithmic expertise to internationally used visual technologies. It also raises important questions about how research organisations preserve openness when commercially valuable techniques are developed.

Visual computing also encompasses deliberately non-photorealistic images, where the objective is communicative or artistic expression rather than physical imitation. Drawings, paintings and animated sequences often use simplified contours, selective shading and stylised movement to communicate meaning. Algorithms that merely imitate photographic detail may therefore be unsuitable for reproducing a chosen artistic style. Daniel Sýkora and collaborators at the Czech Technical University contributed research on example-based stylisation, animated imagery and graphical control of appearance. These investigations considered how attributes of a reference image or style could be transferred while preserving meaningful scene structure. The challenge is especially demanding in video because visually plausible individual frames may flicker when displayed in sequence. Temporal coherence therefore becomes a central scientific criterion, alongside local appearance and an artist's ability to intervene. Later work included diffusion-based image analogies and new tools for controlling expressive visual results. The research demonstrates that creativity and computation are not opposing categories when algorithms expand the choices available to human authors.

Computer-generated images increasingly interacted with moving pictures, sound, immersive environments and collaborative multimedia production during the 2000s and 2010s. A multimedia system is not simply a collection of files because visual, acoustic and interactive events must remain synchronised. Virtual reality requires the representation of an environment that responds to the viewer's movement and perceptual expectations. Augmented reality adds the problem of aligning digital content with real objects and the geometry of the surrounding world. Czech university groups explored virtual and mixed reality, three-dimensional

presentation and techniques for interactive scene manipulation. The Department of Computer Graphics and Interaction also maintained links with artistic practice through the Institute of Intermedia. That environment connected computation with performance, installation art, motion capture and electronic media. Its importance lies in the exchange between technical research and forms of creative experimentation that reveal unfamiliar usability problems. An immersive display may be technically sophisticated yet unsuccessful if it causes discomfort or obscures essential information. Consequently, the evaluation of multimedia innovation requires attention to human perception as well as rendering performance.

Scientific visualisation differs from decorative illustration because its representations are expected to reveal patterns or uncertainties within measured and computed data. Complex simulations can generate numerical fields whose essential relationships are difficult to interpret through tables alone. Three-dimensional volume rendering, interactive views and carefully designed colour mappings may make otherwise hidden spatial structures perceptible. Such tools are particularly useful in physical simulation, medical imaging, molecular research and engineering. Yet misleading choices of scale or colour may create apparent features that are not supported by the underlying measurements. Visualisation research therefore concerns the relationship between data representation, perceptual judgement and scientific inference. Czech computer graphics groups investigated methods relevant to volumetric data, complex scenes and the presentation of spatial relationships. These approaches complemented the country's advances in large-scale computation without being reducible to its supercomputing hardware. The purpose of scientific visualisation is to improve critical analysis, not to replace quantitative evidence with an attractive image.

Human–computer interaction supplies an essential corrective to accounts of technology that concentrate exclusively on algorithms and hardware. Its central concern is how human abilities, expectations and limitations shape the design and use of interactive systems. Czech research at the Department of Computer Graphics and Interaction included work on multimodal interfaces, mobile interaction and accessible design. Pavel Slavík and Zdeněk Míkovec were associated with investigations addressing interaction under diverse practical conditions. Users may interpret visual layouts differently depending on age, visual acuity, experience and surrounding distractions. A technically correct interface can still fail if its controls are difficult to discover or if feedback arrives too late. Research methods therefore require observation, interviews, controlled experiments and iterative evaluation with actual participants. Such human-centred evidence complements performance metrics traditionally used in computer vision and graphics. It establishes usability and accessibility as substantive engineering and scientific criteria rather than cosmetic additions to finished software. Within the Czech research environment, these concerns helped connect visual technologies with public-facing applications.

Navigation technology for people with visual impairments offers a particularly instructive Czech example of research grounded in user experience. Jan Balata, Jakub Franc, Zdeněk Míkovec and Pavel Slavík investigated collaborative navigation and the exchange of spatial knowledge among visually impaired pedestrians. Their 2014 study combined qualitative and quantitative evidence concerning how users communicate about routes and unfamiliar environments. The research questioned the assumption that conventional maps and geometric shortest paths provide

adequate navigation instructions for everyone. Environmental landmarks, audible cues and descriptions of obstacles may matter more than information that is obvious to a sighted traveller. Subsequent research investigated landmark-enhanced route itineraries and ways of communicating relevant details through appropriate interfaces. These studies demonstrate that an advanced visual information system may require non-visual forms of interaction to become genuinely accessible. They also show how local empirical research can contribute to general questions about spatial cognition, language and assistive technology. Here, innovation depends upon the relationship between computational representation and users' lived experience.

Digital cultural heritage provides another setting where image processing, graphics and human interaction meet in a single research workflow. Photographic collections, architectural objects and historical artefacts can be documented through digital imaging and three-dimensional acquisition. Reconstruction may help researchers study spatial arrangements that are difficult to access physically or that have changed over time. Interactive visualisations can also support museum interpretation, educational exhibitions and remote public engagement. However, a plausible digital reconstruction must not be presented as an unequivocal historical record when its geometry contains inferred or missing details. Researchers need documentation of acquisition methods, processing choices and the provenance of source material. The same distinction applies to digital restoration, where an aesthetically convincing result may conceal interpretative decisions. Czech expertise in geometry, visualisation and interface design offers methods potentially useful in heritage research, but particular applications require separate historical verification. This field reveals how computational imagery can enlarge access to cultural knowledge while generating new responsibilities concerning evidence and authenticity. Its development also illustrates the broader relevance of visual computing beyond the industrial sectors usually emphasised in innovation policy.

By the early 2020s, visual computing was undergoing another transformation as foundation models and generative systems became more prominent. Image synthesis and recognition could increasingly be connected with textual descriptions and other forms of contextual information. Neural models improved performance in numerous tasks, but their outputs also introduced difficulties involving reproducibility and the origin of training data. Geometry-based reasoning remained important where exact camera pose, spatial measurement or physically interpretable reconstruction was required. Physically based rendering continued to matter whenever material appearance and illumination had to be estimated or predicted rather than merely imitated. Research on diffusion-based stylisation showed how new models could enter artistic workflows without making human direction irrelevant. Medical and industrial applications continued to demand independent testing because visually plausible model outputs could nevertheless be incorrect. The emerging agenda therefore combined learning, geometry, uncertainty estimation and human oversight. Czech research inherited strong foundations in several of these areas and participated in wider international methodological change.

The geographical distribution of Czech visual computing demonstrates both concentration and meaningful diversification. Prague remained especially important through the Czech Technical University and Charles University, which supported complementary approaches to vision and graphics. Brno provided further expertise in industrial vision, visual sensing and applied

multimedia technologies through its technical university and related laboratories. Other universities and research institutions offered specialised activities in computer graphics, digital imaging and interfaces without necessarily developing identical research profiles. Collaboration across disciplines was particularly important where visual methods had to be tested against medical, engineering or cultural requirements. International mobility also shaped scientific careers, and some influential work by researchers with Czech backgrounds was completed at foreign institutions. Institutional affiliations at the time of publication therefore matter when evaluating the development of national research capacity. An accurate history avoids treating all outputs by Czech-born researchers as results of Czech laboratories.

The most durable achievements of Czech computer vision and graphics between 1993 and 2025 cannot be reduced to impressive images or isolated technological products. Research on robust image regions, geometric estimation, reconstruction and tracking helped develop methods for interpreting difficult visual observations. Biomedical image registration demonstrated how mathematical innovations could support clinical and experimental work under demanding uncertainty. Physically based rendering and stylisation extended the ability to construct convincing or expressive visual worlds through algorithmic design. Human–computer interaction research widened the criteria of technical success to include accessibility and lived experience. These directions were supported by research schools capable of sustaining specialised expertise while participating in international scientific collaboration. Their practical applications also exposed limitations that pure laboratory evaluation could not always anticipate. The record therefore illustrates innovation through reciprocal exchanges between mathematics, software, experiment, industry and human needs. By 2025, Czech visual computing had become a recognisable component of the wider European research environment without losing the distinct disciplinary strengths of its institutions. Its central lesson is that reliable digital imagery depends as much on critical interpretation and methodological validation as on the computational power used to create it.

Robotics, Intelligent Control, Embedded Systems and the Internet of Things

The evolution of robotics in the Czech Republic between 1993 and 2025 is best understood as the convergence of control theory, computing, mechanical engineering and increasingly autonomous decision-making. Robotics concerns embodied systems that perceive their surroundings, select actions and influence a physical environment through actuators, rather than merely process information in software. Automatic control provides mathematical principles for maintaining desired behaviour when disturbances, measurement errors or uncertain operating conditions complicate a task. Embedded computing supplies the processors, communication interfaces and time-sensitive software through which those principles are realised in functioning machines. The Internet of Things extends the field by connecting instruments, controllers and devices to networks capable of exchanging operational data and coordinating decisions. Cyber-physical systems then integrate these computational relationships with the dynamics of physical

equipment, often across production lines or geographically distributed installations. These domains overlap, but their scientific achievements should not be mistaken for interchangeable inventions or for routine purchases of industrial machinery. A new navigation algorithm, a verified scheduling method and a commercial robot installation represent distinct forms of contribution requiring different kinds of evidence. This chapter therefore examines the Czech trajectory through research problems, identifiable publications, institutional development and experimentally grounded applications during the defined historical period.

The independent Czech Republic inherited a developed tradition of cybernetics, instrumentation, electrical engineering and automation that had taken shape within Czechoslovak universities and research institutes. Such expertise included mathematical system models, feedback regulation, industrial measurement, control of electric drives and computational methods for manufacturing equipment. The preceding political system had maintained strong links between technical research and industrial production, although those relationships operated within centrally planned priorities and constrained international exchanges. Laboratories could accumulate experience with machinery and control technologies even when access to advanced electronic components or foreign software was uneven. After the political transformation of 1989, researchers encountered broader opportunities to publish internationally, modernise computing equipment and collaborate with private enterprises. The dissolution of Czechoslovakia in 1993 altered institutional jurisdiction without erasing the expertise preserved in faculties, laboratories and professional networks. Earlier control techniques consequently remained relevant, while international microelectronics and computer-based engineering expanded the practical possibilities of their implementation. Market restructuring also exposed a difference between producing specialised equipment for designated domestic customers and developing competitive, maintainable systems for changing industrial requirements. The emerging national research environment had to support fundamental inquiry as well as applications under substantially different economic conditions. Historical continuity was therefore the foundation for Czech robotics, not evidence that the discipline began only when contemporary autonomous machines became publicly visible.

During the 1990s, robotics research was distributed among technical universities and institutes concerned with system theory, applied mathematics, electronics and machine construction. Prague offered a particularly dense environment through the Czech Technical University, where cybernetics, electrical engineering and computing could be studied within connected technical disciplines. Brno sustained complementary strengths through its technical university and through engineering enterprises requiring automation, sensing and industrial control. The Institute of Information Theory and Automation of the Czech Academy of Sciences preserved a research orientation towards decision-making, system identification, optimisation and mathematical modelling. Regional engineering faculties also supplied skills in mechatronics, instrumentation and programmable control, although their resources and research profiles differed considerably. These institutions were not isolated centres developing identical machines, because their expertise ranged from abstract controllers to production equipment and autonomous platforms. International programmes and visiting researchers gradually reinforced relations with laboratories beyond the former federation. At the same time, the expansion of

personal computing lowered the cost of programming controllers, processing sensor readings and conducting computer-based experiments. Robotics increasingly became a field in which scientific propositions could be tested through accessible experimental platforms rather than only through expensive industrial installations.

A central intellectual problem of automatic control is to determine which actions will make a dynamic system behave reliably despite disturbances and incomplete information. Classical feedback controllers remain important because many physical processes can be regulated using carefully measured errors between desired and actual states. More complicated robots, however, possess coupled mechanical motions, nonlinear responses, actuator limits and uncertain interactions with their surroundings. Their controllers must account for these properties rather than assume that each motor or joint acts independently of the rest of the machine. Czech researchers in system science investigated mathematical models, estimation methods and optimisation procedures applicable to these difficult problems. Model predictive control is one especially useful approach because it repeatedly optimises a future sequence of actions and updates the plan as fresh observations arrive. Such methods can take physical constraints into account, but their effectiveness depends upon the realism of the model and the computational time available for each decision. A controller that provides excellent simulated performance may fail on equipment if delays, friction or unexpected loads have been inadequately represented. Consequently, research quality must be assessed through theoretical properties and reproducible physical experiments, not solely through the sophistication of an optimisation formula. The Czech experience illustrates the enduring connection between mathematical control theory and the practical engineering of reliable automated machinery.

System identification supplies another bridge between mathematical theory and physical robots by estimating how a machine responds to its control inputs. In a laboratory, researchers may determine parameters from carefully designed experiments and then compare predictions with observed trajectories or sensor measurements. In a factory, the same task becomes harder because equipment ages, payloads change and production cannot always be interrupted for calibration. Adaptive control addresses aspects of this difficulty by modifying a controller when evidence suggests that the underlying system has changed. Robust control instead seeks acceptable performance across an explicitly defined range of modelling errors and external disturbances. Neither approach eliminates uncertainty, and a useful design often combines estimation, safety limits and conservative fallback behaviour. The distinction is important for mobile robots because the controlled system includes both the machine and a surrounding environment that cannot be completely specified beforehand. Czech university laboratories gradually combined such methods with better processors and digital sensors, extending their range of realistic experiments. The resulting achievement was frequently a more reliable method of maintaining motion or estimating state, rather than the creation of a visibly different robot.

Autonomous mobile navigation introduces a different class of scientific questions because the robot must choose where to travel without possessing complete advance knowledge of the environment. Localisation asks the machine to estimate its position, while mapping constructs a representation of relevant surroundings from incomplete observations. Planning converts that representation into a feasible route, and control then attempts to execute the route despite

disturbances and obstacles. The individual stages are coupled because an error in perception can make a geometrically attractive route unsafe or impossible to follow. Researchers associated with the Czech Technical University developed expertise in mobile robotics, multi-goal routing, exploration and autonomous monitoring. Such work uses geometric reasoning and computational optimisation to address routes that must visit many locations under energy, curvature or time restrictions. Algorithms for these problems may be theoretically demanding even when the final demonstration resembles an ordinary vehicle moving across a floor. Field validation is especially valuable because terrain, weather and human activity expose limitations that simplified indoor experiments may conceal. Czech contributions to navigation therefore belong to both algorithmic computer science and the engineering of robots operating in imperfect environments. The originality of each result lies in its specified planning or estimation problem, comparative evidence and identifiable contribution to existing methods.

Work associated with Jan Faigl illustrates how robotic planning can be studied as a family of constrained optimisation problems rather than a single task of avoiding obstacles. A monitoring robot may need to visit dispersed locations repeatedly, select informative measurement positions or travel through regions with difficult terrain. An aerial vehicle adds limits on manoeuvrability and flight duration, while a wheeled robot must account for traversability and possible dead ends. These constraints can turn apparently simple route choices into computationally difficult problems involving trade-offs between distance, coverage and risk. The Czech Technical University's research portfolio includes mobile robotics, multi-goal planning, autonomous field navigation and persistent environmental monitoring. The practical value of these investigations is their ability to convert the goals of a mission into explicit quantities suitable for algorithmic analysis. Some methods exploit approximations or heuristics because exact solutions are computationally unreasonable for large instances under real-time conditions. A carefully designed approximation may therefore be scientifically significant when its limitations and performance can be demonstrated. This planning tradition also supports cooperative robotics, where a task must be divided among several vehicles without creating unnecessary travel or unsafe interference.

Long-term robotic autonomy requires a machine to recognise that an environment changes even when its underlying geometry appears relatively stable. People enter and leave rooms, corridors become obstructed, lighting follows daily cycles and objects move between familiar positions. Static maps are therefore insufficient if the robot must operate over weeks or months without constant human correction. Tomáš Krajník and his collaborators developed Frequency Map Enhancement (FreMEn), an approach that models periodic aspects of environmental change using frequency-based representations. Instead of memorising every observed state independently, the method identifies recurring temporal patterns and uses them to predict likely future conditions. Its importance lies in connecting probabilistic environmental modelling with the practical requirements of localisation, mapping and movement planning. Experiments reported in the original paper extended over long periods, providing stronger evidence than a single short demonstration in a controlled laboratory. Such research illustrates how Czech institutions participated in internationally collaborative robotics through methods addressing a precisely defined scientific limitation. FreMEn should nevertheless be understood as a

framework for representing temporal environmental change, not a guarantee that every unexpected event can be anticipated. The continuing challenge is to combine learned regularities with rapid responses when unfamiliar circumstances invalidate earlier predictions.

The temporal perspective developed further in research on long-term visual navigation and the adaptation of robot maps to changing surroundings. A navigation system may recognise the same passageway differently under morning sunlight, evening illumination or seasonal vegetation. If obsolete visual features remain in the map indefinitely, accumulated information can actually reduce rather than improve reliability. Research connected with the Czech Technical University therefore explored strategies for choosing useful features, removing outdated observations and predicting the appearance of familiar places. Teach-and-repeat approaches offer an instructive alternative to navigation systems that continually reconstruct a complete geometric position from scratch. In these systems a robot records a route during an initial demonstration and subsequently uses camera information to correct its motion while repeating the path. A theoretical analysis can establish conditions under which errors remain bounded, making mathematical reasoning part of an apparently practical driving task. Long-term navigation also requires decisions about when the robot should explore again and when existing knowledge is sufficient for the intended mission. The resulting research programme links perception, temporal statistics, computation and control without treating autonomous movement as a purely visual recognition problem.

Human-populated environments introduce a social dimension into robotics because people do not move like predictable mechanical obstacles. A service robot must anticipate that individuals may stop, change direction or behave differently in crowded and quiet periods. Human-aware planning therefore considers not only geometric clearance but also predictability, comfort, communication and the possibility of safe interruption. Temporal models of pedestrian flows can help robots select less disruptive routes, although any inferred routine remains uncertain and context dependent. The value of this research depends upon distinguishing patterns supported by observations from unjustified assumptions about particular individuals. Projects involving long-term autonomous robots have consequently explored how environment models can adapt as habits and operating conditions change. Human–robot interaction also requires clear mechanisms for intervention when a machine's planned behaviour is inappropriate for the circumstances. In medical facilities, public buildings and laboratories, physical safety and the protection of recorded information become equally relevant design concerns. Research on usable robotic autonomy should therefore measure how a machine behaves over extended operation, not merely whether it completes an isolated navigation benchmark. This perspective makes reliability and responsible deployment intrinsic to the scientific problem rather than administrative additions after engineering work is complete.

Research on teams of small aerial robots became a particularly visible area of Czech scientific specialisation during the 2010s and early 2020s. A single unmanned aircraft can inspect a local site, but multiple coordinated vehicles may cover larger spaces or perform observations from complementary viewpoints. Coordination introduces difficult questions about collision avoidance, distributed localisation, communication limitations and the sharing of incomplete sensor information. The Multi-robot Systems group at the Czech Technical University in Prague,

led by Martin Saska, developed research in cooperative flight, trajectory planning and autonomous aerial deployment. Its investigations address conditions in which satellite navigation may be unavailable and obstacles prevent simple pre-programmed paths. Instead of assuming a perfectly connected network, experiments must consider delays or gaps in communication while keeping the vehicles safely separated. The algorithms also have to run onboard aircraft with severe constraints on processor capacity, energy reserves and payload mass. This combination of control theory, estimation and embedded computation explains why aerial robotics cannot be reduced to remote piloting or commercially available drone hardware. Czech achievements are most clearly demonstrated by experimentally tested methods for maintaining reliable group behaviour under demanding physical conditions.

A significant practical result of this research was the development of the Multi-robot Systems (MRS) Drone platform for repeatable deployment of autonomous aerial robot groups. Heřt and colleagues described a modular system intended for real-world operation in varied indoor and outdoor environments rather than a single scripted laboratory demonstration. Its modularity concerns the combination of hardware, sensing, software and control components that researchers can adapt to distinct missions. Common interfaces make it easier to compare guidance algorithms and experiment with several vehicles without rebuilding the entire technical architecture. Reliability requires attention to state estimation, flight control, safety supervision and the consequences of unexpected sensor or communication failures. The platform also illustrates the scientific importance of engineering reproducibility, because a proposed method is more credible when others can reproduce its operating conditions. Such systems create links between fundamental research and the training of researchers who must understand both algorithmic principles and physical equipment. Their applicability extends to inspection, mapping and environmental monitoring, but each proposed use still requires task-specific validation. A modular platform should therefore be assessed as enabling infrastructure for experiments rather than as proof that every application has already been mastered. This distinction protects the analysis from equating the number of potential use cases with independently verified technological achievements.

Decentralised aerial coordination seeks to keep a group functional even when it lacks a permanent command centre or an ideal communication channel. A formation may need to alter course when one vehicle detects an object or when an obstacle obstructs part of the group. Distributed rules allow individual aircraft to respond to nearby observations while preserving a coherent collective objective. Horyna and colleagues investigated swarm navigation for search-and-rescue scenarios using local visual communication and onboard image observations. The reported work examined group behaviour in demanding outdoor conditions through simulations and physical experiments rather than relying on theory alone. Its significance derives from the relationship between local decision rules and emergent collective behaviour, a central problem of multi-robot research. However, decentralisation does not automatically imply superior robustness, because local sensing limitations may propagate inaccurate decisions through an entire formation. Effective evaluation must therefore test obstacle density, sensing errors, communication loss and recovery from unexpected behaviour. The Czech research

demonstrates how scientific advances in robot coordination can be meaningful without claiming that fully autonomous emergency response had become routine by 2025.

Autonomous aerial systems also offer applications where human access is dangerous, costly or physically impractical, including the digital documentation of large historic interiors. Such settings combine restricted flight space, delicate objects, irregular geometry and sometimes unreliable external positioning signals. A group of aerial platforms may acquire complementary photographs or spatial observations while controlling its distance from architectural features. Petráček and colleagues examined cooperative aerial autonomy for documenting difficult-to-access areas of cultural monuments. The scientific problem extends beyond capturing attractive imagery, because the machines must plan coverage and avoid collisions while collecting information suitable for later processing. Accurate documentation also depends upon the calibration of instruments and the ability to relate measurements from several moving viewpoints. Cultural-heritage applications reveal a valuable intersection between robotics, spatial computing and the requirements of preservation specialists. They do not imply that robots replace human judgement about conservation priorities or the interpretation of historic fabric. Rather, well-designed autonomous platforms can make particular recording operations more repeatable and reduce risks associated with manual access. This case illustrates how Czech research connected advanced robotic methods with a practical problem outside the conventional manufacturing environment.

The 2019 performance of the Czech Technical University team in the United States Defense Advanced Research Projects Agency (DARPA) Subterranean Challenge offered another documented test of robotic cooperation. During the tunnel circuit in August, the Czech Technical University Centre for Robotics and Autonomous Systems (CTU-CRAS) group entered robots into an environment designed to resemble difficult underground search conditions. The university reported first place among teams without direct programme sponsorship and third position overall in that circuit. The challenge required teams to locate designated signs or objects while navigating confined spaces where communication and localisation were difficult. Its research relevance lay in integrating several subsystems under conditions that did not resemble an orderly university laboratory. Mobile robots had to collect observations, interpret uncertain terrain and transmit useful information despite operational constraints. Competitive success, however, should not be confused with a general demonstration that rescue robots can replace emergency personnel in all settings. The event instead provided externally organised evidence that a Czech research team could combine autonomy, mapping and multi-robot coordination effectively. Such evidence supplements peer-reviewed publications by exposing complete systems to tasks and constraints selected independently of their developers.

Open technical platforms, shared experimental data and reusable software became increasingly important to the credibility of robotics research during the period. An algorithm tested only on a unique, poorly documented machine is difficult to evaluate independently from the capabilities of its hardware. Standardised middleware can separate sensor acquisition, planning, state estimation and control into components that interact through explicit interfaces. Research teams still need to verify how network latency and scheduling affect these interfaces when a robot operates under real-time constraints. The use of openly described platforms such as MRS Drone

strengthens reproducibility by allowing different investigators to compare approaches against related technical conditions. Open development also supports scientific training because students can examine actual implementations rather than reconstruct algorithms from abbreviated descriptions. Nevertheless, software availability alone does not establish that a control method is safe on every airframe or in every environment. Responsible replication requires documentation of physical parameters, emergency procedures, hardware dependencies and the circumstances under which experiments were conducted. Czech research demonstrates the increasing value of engineering infrastructure that helps translate original ideas into independently testable robotic systems. It also highlights the continuing distinction between an open prototype and an industrial product maintained throughout a defined service life.

Industrial robotics in Czechia developed within an economy possessing strong traditions in machinery, automotive production, precision manufacturing and electrotechnical engineering. Automated arms and programmable machinery can support repetitive operations, but the deployment of industrial robots does not itself constitute original scientific research. Relevant scientific questions concern accuracy, energy use, vibration suppression, safe cooperation, task scheduling and adaptation to variable production conditions. For a manipulator with several linked joints, movements at one point may affect forces and permissible accelerations elsewhere in the structure. A digital controller must therefore coordinate mechanical geometry, actuator characteristics and process requirements rather than simply send independent position commands. Collaborative industrial applications add the difficulty of detecting human presence and selecting reactions that avoid dangerous contact. Researchers have also considered how robots might be reconfigured for short production runs instead of operating exclusively in fixed, high-volume installations. These questions gained visibility as Czech manufacturing faced pressure for higher flexibility, tighter quality requirements and greater integration of engineering data. The distinction between scientific method and production practice is essential when attributing innovation to national research groups or industrial suppliers.

Research undertaken by Květoslav Belda at the Institute of Information Theory and Automation illustrates a substantive Czech contribution to industrial motion control. His work considered model-based and energy-aware control of articulated robotic mechanisms, with particular attention to the optimisation of trajectories and actuator behaviour. A model predictive controller estimates the consequences of candidate motions over a moving horizon and repeatedly recalculates its instructions as a robot progresses. This approach can represent constraints and objectives that conventional fixed control rules find difficult to accommodate within one formulation. Belda's published account of nonlinear model predictive algorithms addressed their application to industrial articulated robots. The institute also documents work on smoothing motion paths and reducing the energy demands of complex robotic mechanisms. A scientifically credible assessment distinguishes theoretical optimisation criteria from measured savings obtained on a specified machine under actual operating conditions. Physical experiments remain necessary because unmodelled friction, changes in load and actuator limitations can affect the performance of an otherwise plausible controller. This line of work demonstrates that innovation in robotics may be found in control laws and mathematical modelling even when the mechanical

platform remains recognisably conventional. It also connects the Czech tradition of system science with international research on efficient and reliable automation.

Embedded systems impose requirements different from those found in ordinary desktop software because they interact with physical processes that cannot wait indefinitely for computation. A controller may need to sample a sensor, process information and update an actuator within a strict deadline to preserve stable machine behaviour. In a safety-critical application, arriving at the correct answer too late can be equivalent to producing an incorrect command. Scheduling theory therefore becomes part of robotics engineering, especially when several tasks compete for a processor or share a communication network. The Industrial Informatics Department at the Czech Institute of Informatics, Robotics and Cybernetics (CIIRC) identifies real-time scheduling, operating systems and formal verification among its core research topics. This research also examines multicore and heterogeneous computing platforms, where greater available processing power introduces more complex timing interactions. Predictability is particularly important for vehicle electronics, industrial controls and robotic systems that combine rapidly changing inputs with bounded computation. Formal methods can establish properties of some software components, but complete safety also depends upon sensors, electrical interfaces and physical testing. Czech contributions in this area bridge theoretical scheduling and the engineering realities of embedded cyber-physical machines.

The growth of networked sensors and embedded controllers gave the Internet of Things a practical role in industrial automation during the 2010s. A connected device may transmit temperature, vibration, position or energy-consumption data to a local controller or a larger monitoring system. When these measurements are used only for reporting, the system remains different from an autonomous controller that changes physical behaviour. More advanced architectures support local inference and rapid actuation while sending longer-term records to analytical services beyond the production machine. Edge computing can reduce communication delay and protect continuity of operation when a connection to a distant data centre is interrupted. Yet distributing decisions across devices raises questions about clock synchronisation, communication reliability and consistency between different interpretations of system state. An industrial network must also establish what happens when a sensor fails or sends data outside its plausible operating range. Research on embedded and cyber-physical architectures seeks explicit guarantees about such conditions, rather than assuming that additional connectivity necessarily improves production. The central contribution of networked robotics lies in designing dependable relationships between information, computation and physical action. This is why Internet of Things deployments require interdisciplinary evaluation involving control engineers, software specialists and domain experts.

Brno became an important centre for industrial cybernetics through research combining electric drives, advanced control, sensing and robotics. The Central European Institute of Technology at Brno University of Technology strengthened this profile through its Cybernetics and Robotics group led by Pavel Václavek. The group's stated focus encompasses intelligent control systems, robotic technologies, embedded devices and sensing for industrial and mobility applications. Earlier work in electrical engineering supplied expertise needed for efficient drive control and

mechatronic integration, while later programmes expanded towards autonomous machinery. The institute reported an explicit extension of its robotics research orientation in 2021, linked partly to the establishment of a research testbed for advanced production. This development illustrates how a research centre can broaden its scientific profile without abandoning its underlying engineering specialisation. Research in electromobility and automation, for example, requires reliable electronic controllers capable of responding to changing loads and power constraints. Experiments with mobile robotic platforms can combine these motor-control techniques with navigation and local perception. Brno's role therefore cannot be reduced to a secondary location for projects designed elsewhere, because its distinctive competence lies in integrating control research with industrial technology.

The Research and Innovation Centre on Advanced Industrial Production, known as RICAIP, represents a significant institutional response to the demand for integrated robotics research. Developed through cooperation between Czech and German partners, the initiative connects the Czech Technical University, Brno University of Technology and institutions in Saarbrücken. The centre's international project began in September 2019, and its planned work extends beyond the endpoint of this book's historical analysis. Its distributed experimental approach combines testbeds in Prague, Brno and Germany to investigate advanced manufacturing and related software and control systems. Such facilities can reproduce relationships between robots, production equipment, digital planning services and manufacturing data under controlled conditions. Their scientific advantage lies in permitting modifications and measurements that would be prohibitively disruptive on a commercial production line. The initiative also illustrates how European research funding can support shared national capabilities without requiring every partner to possess identical laboratory equipment. Experimental collaboration, however, should not be described as proof that all proposed industrial solutions were already operating commercially by 2025. The institutional achievement is the establishment of a research environment in which advanced robotics and intelligent industrial production can be systematically developed. Its longer-term impact depends upon the quality of resulting methods, sustained access and transfer into independently validated applications.

Industrial testbeds are particularly useful when the behaviour of a system emerges from interaction among many individually familiar technologies. A connected workshop may contain robotic arms, transport vehicles, manufacturing machines, process sensors and software coordinating their activity. The difficulty lies not merely in connecting these components but in ensuring that the resulting production workflow is reliable under changing orders and conditions. A digital twin can represent selected aspects of equipment and processes for simulation, diagnostics or planned modification. Such models are useful only when their assumptions are explicit and measurements can reveal departures from actual machine behaviour. The Prague experimental infrastructure associated with CIIRC has incorporated work on robotics, digital twins, industrial data and edge computing. Testbeds provide opportunities to compare alternative production arrangements before costly physical reconfiguration, particularly in settings involving smaller and more variable product batches. Human operators remain important because production tasks include informal knowledge and exceptions that an automatic planning system may not anticipate. Consequently, research must assess throughput

and energy efficiency alongside safety, maintainability and the practical organisation of human work.

Human–robot collaboration changes the meaning of industrial automation by moving away from a strict separation between automated machinery and human workers. A collaborative robot may share a workspace with a person, but physical proximity is not in itself proof of safe or productive cooperation. Risk assessment must consider movement speed, reachable forces, unexpected starts, failure recovery and the tasks undertaken by both participants. Perception technologies can provide information about occupied spaces, while control systems can limit motions when conditions become uncertain. A robot's contribution may consist of precise positioning or repetitive handling while a skilled employee retains responsibility for inspection and complex judgement. Research within projects such as ROBOPROX investigates safe human collaboration, flexible robot deployment and more autonomous industrial operations. Nevertheless, the existence of a funded project establishes a research agenda rather than demonstrating that all intended techniques have been validated. Successful evaluation should therefore include actual task performance, recovery from faults, human usability and the limits of deployed safeguards. Czech industrial robotics offers a useful case for examining how autonomous systems can complement experienced workers when organisational design receives as much attention as algorithms. The most durable benefits are likely to emerge where technical control and human work are jointly considered rather than managed as unrelated concerns.

Optimising a flexible manufacturing system requires decisions about the allocation of machines, the order of operations and the movement of materials between workplaces. Automated guided vehicles or mobile robots introduce routing and timing constraints that do not exist in a purely stationary production schedule. If two vehicles require the same narrow corridor, a locally efficient plan may cause congestion or a production delay elsewhere. Researchers at Masaryk University investigated this coordination problem in work on scheduling mobile robots for transportation and manufacturing tasks. Their research explored computational approaches suited to complex scheduling environments with alternative assignments and multiple operating constraints. Such problems are often difficult to solve exactly at the scale required by a busy manufacturing facility. Heuristics and mathematical optimisation can be valuable when their results improve feasible schedules within the available computational time. The scientific question is not simply whether automation reduces costs, but which algorithmic decisions remain dependable when production conditions change. This work connects Czech research in operations research to embodied mobile systems and the management of industrial resources.

An instructive example of Czech embedded engineering outside conventional factory equipment is the Turris router initiative developed by CZ.NIC. Although a router is not itself an industrial robot, it shares important engineering characteristics with connected sensing devices, including embedded processors, software updates and network interfaces. The association's research project began in 2013, and later Turris devices integrated open-source software with security-oriented monitoring and maintenance. Researchers at Brno University of Technology participated in hardware design, driver development, testing and related software work for the Turris Omnia platform. The collaboration illustrates how university engineering knowledge can contribute to a real, maintained device rather than remaining confined to an academic demonstration. For

Internet of Things applications, gateway devices must manage heterogeneous endpoints while protecting the integrity of their communications. Update mechanisms and security diagnostics are particularly relevant because unattended devices may remain installed for many years. Nevertheless, the requirements of a household or network router are not automatically equivalent to the deterministic control demands of industrial machinery. This example is therefore best treated as evidence of national competence in embedded and connected systems, with clear limits on claims of direct robotic application. It also demonstrates how open engineering and commercial deployment can coexist within a Czech technology-development ecosystem.

International collaboration altered the scale at which Czech robotics could develop complex experimental platforms and compare scientific results. European research partnerships provided access to specialised expertise in manufacturing technology, embedded electronics, artificial intelligence and industrial measurement. RICAIP established a particularly visible Czech–German network of research and testing facilities directed towards advanced production. Other collaborations connected Czech researchers with international communities concerned with autonomous aerial vehicles, mobile navigation and system safety. Joint projects can increase scientific capability, but attribution requires careful attention to where a particular method originated and which researchers developed or tested it. An internationally co-authored result is not exclusively national simply because one participant held an appointment in Prague or Brno. Conversely, participation by a smaller Czech group should not be dismissed when it contributes an original algorithm or a technically demanding component. Cross-border testbeds also demonstrate that a research infrastructure may function as a distributed network rather than a single geographically concentrated laboratory. The historical significance of this development lies in widening opportunities for distinctive Czech expertise to influence larger technological systems.

Applications beyond manufacturing show both the versatility of robotics and the need to distinguish a promising experiment from routine deployment. In medicine, robotic positioning and instrument guidance require unusually high reliability because errors can have direct consequences for patient safety. Environmental monitoring may tolerate less precise motion but demands extended operation, energy management and robust sensing in outdoor conditions. Precision agriculture combines navigation, perception and intervention with variability in soil, crops, weather and agricultural practice. Infrastructure inspection often requires access to confined or hazardous areas where human entry is difficult or expensive. Czech research in autonomous flight, route planning and sensing provides methods that could support these settings, although validation requirements differ significantly among them. Robots documenting cultural monuments supply a further example of interdisciplinary application, where the relevant result may be measurement coverage rather than manipulation of physical objects. Across these domains, the same general planning idea may require substantial changes in sensors, data interpretation and permitted actions. The research value of a transferable method therefore depends upon recognising which assumptions survive the move between application environments. Effective robotics development joins reusable scientific principles to detailed knowledge of the task in which a robot will operate.

The expansion of robot capabilities between 2021 and 2025 intensified concerns about safety, security, workforce preparation and dependence upon complex software. More capable perception or learned control can improve adaptability, but such components may react unpredictably when confronted with observations unlike those used in development. Consequently, engineers must establish safeguards that do not rely exclusively on the same learning model whose errors they aim to contain. Verification, controlled testing and transparent operating limits are especially important when machines act autonomously near people or valuable equipment. Industrial Internet of Things deployments also create possible points of entry for cyberattacks, making network security relevant to physical safety. Researchers and manufacturers must distinguish secure communication, dependable computation and safe mechanical behaviour rather than treat them as one undifferentiated property. Professional education becomes more demanding because roboticists need to understand mechanics, control theory, programming, experimental methodology and operational risk. Long-term infrastructure support is equally essential since sophisticated testbeds require maintenance, skilled technical staff and reproducible evaluation procedures. Czech initiatives in advanced industrial production and autonomous systems illustrate the opportunities of this convergence while leaving important challenges unresolved by 2025.

By the end of 2025, Czech robotics had evolved from inherited cybernetic and engineering traditions into a diverse field combining control algorithms, mobile autonomy, embedded computation and industrial research infrastructure. Prague developed internationally connected strengths in planning, long-term navigation, aerial multi-robot systems and advanced industrial informatics. Brno contributed particular expertise in sensors, electric drives, technical cybernetics, embedded engineering and manufacturing-oriented experimental facilities. The Czech Academy of Sciences preserved complementary work in mathematical control, dynamic decision-making and the modelling of industrial robotic motion. Concrete research results included temporal environment models, autonomous aerial platforms, scheduling methods and optimisation approaches whose significance can be traced to identifiable studies. Internationally organised trials and shared testbeds supplied forms of validation extending beyond conventional departmental experiments. At the same time, the number of installed machines, announced projects or possible applications cannot replace evidence of original scientific contribution. A balanced assessment must distinguish mathematical invention, experimentally verified engineering, research infrastructure and sustainable commercial adoption. The historical trajectory demonstrates how national scientific traditions can become resources for new technologies when institutions remain open to international cooperation and methodological change. Czech robotics consequently provides a revealing example of innovation arising through the interaction of rigorous research, practical experimentation and the changing demands of a digitally connected economy.

Quantum Computing, Semiconductor Technologies and Emerging Computer Architectures

The development of quantum computing and new processor architectures in the Czech Republic between 1993 and 2025 cannot be described as a simple replacement of conventional electronics by quantum machines. It is better understood as the convergence of several traditions that had previously progressed along different scientific and industrial paths. Mathematical informatics supplied methods for expressing algorithms and measuring computational complexity, while physics investigated the conditions under which information could be encoded in quantum states. Microelectronics contributed the materials, fabrication processes and electronic circuits needed to construct devices that could operate reliably outside a laboratory demonstration. Computer engineering, meanwhile, developed ways of coordinating processors, memories, sensors and software under increasingly demanding constraints on energy consumption. Czech research institutions inherited expertise in all these areas from the Czechoslovak period, although their resources and international connections changed markedly after independence. The enlargement of European research programmes subsequently allowed specialised domestic groups to participate in investigations that would have exceeded their national infrastructure alone. By 2025, the research landscape included sophisticated quantum-optical experiments, university-based processor design, semiconductor manufacturing and a newly inaugurated quantum computing installation. The significance of these developments lies not in claiming that every technology originated in Czechia, but in explaining how local intellectual and industrial capabilities became connected to emerging European technological systems. This chapter therefore examines scientific contributions, engineering methods and strategic infrastructure as different, complementary forms of innovation.

A crucial distinction separates quantum information research from the operation of a commercially supplied quantum computer. Quantum information theory investigates the representation, transformation and measurement of information according to the mathematical principles of quantum mechanics. Quantum computing narrows that investigation towards operations capable of implementing algorithms on controllable physical quantum systems. Quantum communications and sensing share important theoretical foundations with computation, but they pursue different practical objectives and should not be counted automatically as achievements in quantum processing. Classical computer architecture poses a related but distinct set of problems concerning instruction execution, memory hierarchies, parallelism and hardware efficiency. Semiconductor engineering concerns the physical materials and manufacturing processes through which electronic functions can be realised. These fields increasingly interact because a useful quantum processor requires classical electronics, precise control, calibration, data handling and integration with ordinary computing resources. Conversely, progress in classical chip design can improve energy efficiency and the practical deployment of artificial intelligence without involving quantum effects as a computational resource. The Czech experience illustrates how a relatively small research system can cultivate meaningful expertise through cooperation across these disciplinary boundaries.

The foundations of this multidisciplinary activity extend beyond the political beginning of independent Czechia in 1993. Czechoslovak universities had developed strong schools in mathematical physics, optics, electronics, cybernetics and electrical engineering, while specialised workplaces possessed practical knowledge of materials and precision instrumentation. Such expertise was important because advanced computing depends upon experimentally controllable physical systems as well as abstract algorithms. Research into quantum phenomena did not begin with contemporary enthusiasm for quantum computers; it had long been part of atomic, optical and condensed-matter physics. Likewise, the design of electronic circuits and digital control devices preceded the emergence of globally marketed processor intellectual property. After the political opening of 1989, international academic mobility and access to equipment broadened the questions that Czech researchers could pursue. New grant arrangements and cooperation with European laboratories encouraged the exchange of methods in quantum optics, chip fabrication and embedded computing. At the same time, the transition to market conditions transformed relationships between semiconductor production, university research and private technological companies. The resulting post-1993 system combined long-standing scientific competence with new opportunities for commercialisation and international specialisation. This continuity is essential to explaining later achievements without mistaking the date of state independence for the birth of the relevant sciences.

Palacký University in Olomouc became one of the most recognisable Czech environments for research connecting quantum physics to information processing. Its Department of Optics developed theoretical and experimental programmes involving photon states, quantum measurements, entanglement and optical transformations. The work of Jaromír Fiurášek, Radim Filip, Miroslav Ježek and their collaborators shows how questions in foundational optics can lead to methods for processing quantum information. Photons are attractive experimental carriers because optical states can be manipulated and measured using well-established laboratory techniques. Yet optical implementations also confront substantial limitations involving loss, imperfect detection, probabilistic operations and the difficulty of scaling interactions between individual photons. The scientific interest of the Olomouc programme consequently rests on investigating what transformations are physically possible, under which conditions they succeed and how their outcomes can be certified. These questions connect formal quantum theory with experimental design rather than treating a laboratory demonstration as an immediately deployable computer. Collaborative publications in international physics journals made the work part of broader discussions on quantum measurement and state engineering. The importance of this school was thus primarily conceptual and methodological, although the techniques also informed future communication and information technologies.

A significant theoretical contribution came from research into the boundaries between Gaussian and non-Gaussian quantum states. Gaussian states are mathematically tractable and experimentally accessible, making them central resources in continuous-variable quantum information processing. However, certain transformations required for more general processing depend on properties that cannot be reproduced solely by mixtures of Gaussian states and operations. In 2011, Radim Filip and Ladislav Mišta proposed a criterion for identifying states that

lie outside the convex set of Gaussian mixtures even when their Wigner function is non-negative. The result addressed a subtle problem because a simple inspection of phase-space positivity does not capture every non-classical feature relevant to quantum protocols. Their approach connected abstract classification with quantities that could be evaluated through photon-number measurements. It thereby demonstrated how a carefully designed mathematical witness can reveal an experimentally meaningful quantum resource. The research did not establish a universal quantum computer, but it clarified conditions under which optical states have properties useful for more ambitious information processing. This distinction between identifying a resource and engineering a scalable machine is fundamental when assessing the Czech contribution. The example also illustrates the importance of distinguishing an experimentally accessible witness from a complete operational description of quantum computational usefulness.

Experimental work in Olomouc similarly addressed whether quantum operations could be implemented through conditional optical arrangements. In 2008, Michal Mičuda, Miroslav Ježek, Miloslav Dušek and Jaromír Fiurášek reported an experimental realisation of a programmable quantum gate. Such a gate illustrates the possibility of changing the action of a quantum device through an appropriately prepared programme state rather than through a wholly rebuilt apparatus. Physical implementations remain constrained by the quantum no-programming principles and by the probabilities associated with measurement-based operations. The scientific achievement therefore concerns a specified transformation under defined experimental conditions, not unlimited programmability across arbitrary states. Related work on teleportation-based programmable gates examined how entanglement and measurement could transfer operations between prepared resources and input systems. These experiments helped clarify the relationship between circuit-level ideas and the physical operations available in linear optics. They also offered graduate researchers experience in designing apparatus, analysing detection events and interpreting fidelity measurements. In this respect, experimental quantum information created methodological continuity between optical physics and the emerging language of quantum computation.

Loss in an optical channel provides another example of a basic physical limitation with direct informational consequences. Photons may fail to reach a receiver because of absorption, scattering or imperfect components, and these losses cannot be ignored in realistic protocols. Researchers in Olomouc and an international collaborator proposed a conditional method using noiseless attenuation before transmission followed by amplification afterwards. In a 2012 publication, Mičuda and colleagues examined how this arrangement could suppress the effective impact of loss without simply introducing extra noise into the encoded quantum state. Their experiment demonstrated the mechanism within a restricted space involving vacuum and single-photon components. The result matters because it connects quantum operations with a clearly formulated problem in communication reliability. It also illustrates why apparent improvements must be analysed probabilistically, since conditional success can come at the price of lower overall transmission rates. The work therefore should not be presented as a general solution to all losses in quantum networking. Its lasting value lies in showing how experimentally testable operations can refine understanding of information transmission under physical constraints. This

result became part of an international discussion about the physical cost and reliability of transmitting fragile optical quantum information.

The scientific significance of quantum measurement becomes particularly clear when researchers attempt transformations that ordinary quantum dynamics prohibit. In 2014, Miroslav Ježek and collaborators demonstrated the conditional orthogonalisation of partly unknown quantum states, including a two-qubit case. The study responded to the impossibility of constructing an exact universal NOT operation for arbitrary unknown qubits. By restricting the available information and applying a suitable quantum filter, the researchers identified circumstances in which a related task could nevertheless be achieved. This did not contradict the no-go theorem because the domain of admissible states and the form of the procedure differed from those of the prohibited universal operation. Rather, the work showed how quantum information theory can turn an impossibility result into a more precise experimental question. Investigations of non-Gaussianity, state preparation and optical measurement developed through similarly careful attention to assumptions. Such achievements are scientifically original even when they yield no immediately marketable device. They strengthen the intellectual foundations on which reliable future quantum technologies may depend.

The transfer from optical demonstrations to processor technology requires a rigorous understanding of computational resources. A qubit can represent coherent superpositions of two logical basis states, but the existence of superposition does not by itself guarantee an advantage over a classical algorithm. Entanglement, interference, coherent control and measurement must be organised within algorithms that address well-defined computational tasks. The cost of physical gates, error rates, connectivity and data transfer can determine whether a proposed quantum procedure is practical. Researchers therefore distinguish algorithmic complexity on an ideal model from runtime and accuracy on an actual machine. Some widely discussed examples, including quantum search and integer factorisation, illustrate possible speed-ups under explicit mathematical assumptions. Their existence does not imply that present-day noisy processors can solve any real industrial problem faster than modern classical systems. Czech teaching and research communities increasingly incorporated these distinctions into programmes spanning theoretical informatics, mathematical physics and experimental optics. The development of such expertise became important when national institutions later sought to operate shared quantum hardware rather than study quantum principles in isolation. For this reason, methodological training must address both the mathematical description of a protocol and its actual experimental resource requirements.

Prague provided another environment in which mathematical methods, physics and quantum information could interact. At the Czech Technical University in Prague, work and education connected quantum optics, quantum communication and the foundations of quantum algorithms with a broader engineering curriculum. Research on quantum walks and the dynamics of quantum systems illustrates how concepts from graph theory and mathematical analysis can enter investigations of quantum information. The mathematical structure of a walk determines possible interference patterns, while its physical realisation introduces additional constraints on coherent evolution. This interaction makes quantum computation particularly instructive for a technical university because theoretical models must eventually be related to controllable

devices. Theoretical contributions also require cautious interpretation, since a new analytical result or simulation is not the same as the construction of a fault-tolerant processor. Cooperation among Prague, Olomouc and other domestic centres helped connect different kinds of expertise. International publications and specialised doctoral education supported the circulation of ideas beyond national boundaries. By the early 2020s, Czech researchers were better prepared to evaluate claims about quantum algorithms because their expertise extended across theory, measurement and computing infrastructure.

Quantum information research has also influenced the study of secure communications without making quantum computers equivalent to cryptographic networks. Quantum key distribution uses properties of quantum states to support particular key-establishment protocols whose security depends upon both theory and implementation. Experimental performance is affected by detector behaviour, channel losses, authentication and the engineering of optical links. Czech activity in this area drew on the Department of Optics in Olomouc, relevant Academy institutes, technical universities and the national academic networking environment. Collaboration across these institutions was significant because no single discipline could supply the optics, communications engineering and security analysis required for a national experimental network. Such work connects quantum information with a public-interest need for trustworthy infrastructure. However, quantum key distribution does not remove the necessity for conventional network management, trustworthy end points or careful evaluation of system vulnerabilities. Nor does the existence of a quantum communications project prove that a universal quantum computer is available domestically. The research should therefore be recognised as a neighbouring strand of quantum technology with its own scientific and operational standards. These caveats matter especially when governments consider investing in systems expected to secure sensitive digital communications.

This collaborative orientation acquired an institutional form through the Czech National Quantum Communication Infrastructure project, known as CZQCI. Beginning in 2023, the project brought together organisations including Masaryk University, CESNET, the Czech Technical University, Palacký University and the Institute of Scientific Instruments of the Czech Academy of Sciences. Its programme envisaged a backbone connecting Prague, Brno and Ostrava together with metropolitan branches, testing facilities and specialist training. Such a structure was intended to support experiments with quantum key distribution in realistic networking conditions and strengthen connections with European quantum communications initiatives. The proposed network was not simply a purchase of optical equipment, because interoperability, operational procedures and the education of personnel were also central objectives. Its development illustrates the movement from separate laboratory experiments towards coordinated technical infrastructure. At the 2025 endpoint, the appropriate interpretation is that a multi-year deployment and testing programme was under way, rather than that every planned service had been conclusively completed. This chronological caution is necessary when institutional publicity describes future functionality alongside realised milestones. CZQCI demonstrates how national capability can be built around a specialised contribution to a wider European network.

A more visible computing milestone occurred when the VLQ quantum system was inaugurated in Ostrava on 23 September 2025. The installation is hosted by the IT4Innovations National

Supercomputing Center at VSB—Technical University of Ostrava. It was procured within the multinational LUMI-Q consortium through the European High Performance Computing Joint Undertaking, commonly referred to as EuroHPC JU. The system supplied by IQM Quantum Computers uses superconducting technology and contains twenty-four physical qubits. Its architecture connects qubits through a central resonator in a star-shaped arrangement designed to reduce some of the routing operations required by less connected configurations. The project placed Czechia among the European locations hosting a dedicated quantum computing installation financed through shared public investment. Nevertheless, the hardware was supplied by an international company, and the inauguration should not be described as an indigenous Czech invention of superconducting qubits. Nor should the September ceremony be confused with fully established general user access, since calibration and service integration continued beyond the formal unveiling. The central national achievement was the development of hosting, coordination and research capabilities within a European quantum computing infrastructure. This distinction gives the milestone its proper significance without overstating its immediate computational performance.

The VLQ installation also illustrated why future computing environments are likely to combine classical and quantum resources. Classical supercomputers remain essential for preparing inputs, optimising circuits, simulating noise and interpreting measurement data. Quantum devices contribute a different physical resource, but their effective use requires software layers capable of handling queues, jobs, calibration information and hardware-specific limitations. The plan to link VLQ with Karolina in Ostrava and other European high-performance computers recognised this practical dependence. A hybrid calculation may involve a classical optimiser repeatedly submitting quantum circuits and revising parameters from measured outputs. Such a workflow can be expensive when circuit execution and data transfer involve delays or when noise requires substantial repetition. Hence computational research must investigate the whole system rather than attributing every improvement to the quantum processor alone. Technical progress will be measured through reproducible benchmarks, error-aware scheduling and demonstrable performance on carefully selected tasks. The 2025 installation provided an institutional foundation for such investigations rather than proof that quantum advantage had already become routine.

Superconducting quantum processors pose engineering challenges that connect microelectronics with thermodynamics and precision measurement. Their quantum states require operation at extremely low temperatures, careful shielding and electronic control that limits disturbances to coherence. Gates implemented through electromagnetic signals are affected by calibration drift, unwanted coupling and errors that accumulate across successive operations. The physical layout of a processor therefore influences which quantum circuits can be executed efficiently. VLQ's star-shaped connectivity was intended to reduce the need to exchange the logical positions of qubits during certain calculations. However, advantageous topology cannot independently remove the fundamental challenges of decoherence, measurement error and constrained processor scale. Assessment must also distinguish physical qubits from error-corrected logical qubits, because the latter require additional protection and resources. This is one reason why a count of qubits offers only a partial description of scientific

capability. Czech researchers entering this infrastructure had to combine mathematical reasoning with practical knowledge of control systems, materials and experimental calibration. In practice, useful scientific results depend on documenting these limitations as carefully as the nominal design of the hardware.

Semiconductor technologies entered the same historical period through a different lineage associated with manufacturing and industrial electronics. The Czech lands possessed substantial traditions in electrical engineering, materials science and device production before the separation of Czechoslovakia. The post-1993 semiconductor sector nevertheless operated within new ownership structures, international supply chains and rapidly changing global competition. Rožnov pod Radhoštěm retained an important position as a manufacturing and development location associated with silicon processing and electronic components. The local design centre dates its establishment to 1993, while the manufacturing operation later became part of the international corporate structure that evolved into onsemi. The site's development illustrates continuity of industrial capabilities through privatisation, foreign investment and changes in technological specialisation. Such continuity should not be interpreted as proof that Czech institutions independently controlled all design decisions or worldwide distribution channels. It does, however, demonstrate that advanced industrial knowledge, production experience and skilled technical labour survived the post-socialist transformation. This industrial base became especially significant when European policymakers later reconsidered the resilience of semiconductor supply chains.

The relationship between digital computing and semiconductor production extends well beyond the manufacture of central processing units. Memory components, voltage regulators, sensors, interface circuits and power devices are essential to the functioning of contemporary information systems. The efficiency of a computing installation depends not only on the logical design of processors but also on reliable conversion and distribution of electrical power. Semiconductor devices used in data centres can therefore contribute to technological progress through reduced losses and more effective thermal management. Czech manufacturing specialisations have included power-management components and related technologies alongside activities directly connected with digital electronics. The distinction matters because a facility producing advanced power semiconductors should not be described automatically as a factory for leading-edge general-purpose microprocessors. In industrial research, device reliability, material quality, packaging and production yield are often as important as an increase in transistor density. These requirements create connections between solid-state physics, chemical processing, precision measurement and information technology. They also explain why a semiconductor strategy must account for a wider value chain than the design of computing chips alone. Consequently, the material composition and electrical behaviour of support components affect the possibilities of systems whose primary purpose is information processing.

Silicon carbide became a strategically important material because of its properties in high-voltage and high-efficiency power electronics. Compared with conventional silicon in suitable applications, devices based on silicon carbide can support efficient power conversion under demanding electrical and thermal conditions. The material nevertheless introduces difficulties in crystal growth, wafer quality, device fabrication and process control. A commercially viable

production chain requires expertise in substrates, epitaxy, device structures, packaging and testing. In June 2024, onsemi announced that it had selected the Czech Republic for a proposed vertically integrated silicon carbide investment at its Rožnov site. The company described a prospective multi-year commitment of up to two billion United States dollars and connected the plan with electric vehicles, renewable energy and data-centre power needs. This announcement was important evidence of the perceived industrial value of the Czech location and its accumulated workforce. It was, however, a proposed investment, and its stated amount cannot be counted as completed expenditure or installed production capacity by the end of 2025. The distinction between announced plans and verified outcomes is indispensable to an accurate history of semiconductor development.

The increasing political importance of chips led the Czech government to adopt a National Semiconductor Strategy in October 2024. Its objectives included strengthening research, supporting industrial capabilities, improving skills and connecting national organisations to European semiconductor initiatives. The government set goals for expanding sectoral production, increasing export performance and enlarging the specialised workforce by 2029. These targets provided a policy framework rather than a statistical description of achievements already realised in 2024. The strategy also recognised the need to support companies designing components and equipment even when their production depended on facilities abroad. This wider approach reflected the structure of an industry in which design tools, manufacturing machinery, materials, packaging and qualification processes are distributed internationally. A medium-sized country can contribute through selected competencies without maintaining every fabrication technology on its own territory. However, concentration in particular specialisations can leave firms exposed to international demand fluctuations and supplier dependence. The significance of the strategy therefore lies as much in identifying structural vulnerabilities as in setting ambitious quantitative goals. Progress towards the stated objectives consequently depended upon the availability of researchers, specialised suppliers and investment decisions extending beyond the strategy itself.

The creation of the Czech Semiconductor Centre in Brno during April 2025 turned part of the strategy into an institutional undertaking. Established through cooperation between Brno University of Technology and national partners, the centre was intended to connect academic competence with industrial design and development needs. Its planned services included mentoring, access to expertise, support for smaller companies and pathways towards European pilot lines and design infrastructure. Such a competence centre does not itself replace a semiconductor fabrication plant or guarantee that every assisted project will become commercially successful. Instead, it addresses gaps in knowledge transfer, professional networks and access to expensive development processes. These functions are particularly significant for start-ups whose engineers may possess innovative ideas without sufficient resources to fabricate and test prototypes. Linking firms with international facilities can improve their ability to explore specialised architectures or production methods. The centre's inauguration in 2025 was a verifiable institutional achievement, although its longer-term economic impact necessarily remained to be assessed after the period covered here. It

illustrated a strategic shift from isolated capabilities towards a more coordinated national ecosystem.

Research infrastructure in Brno provides an important bridge between this policy ambition and practical scientific investigation. The Central European Institute of Technology (CEITEC) Nano centre, associated with Brno University of Technology, offers shared facilities for nanofabrication, characterisation and the analysis of advanced materials. Its cleanroom laboratories support activities including lithography and the preparation of structures whose dimensions require specialised instrumentation. These resources enable researchers to investigate components and materials relevant to electronic, photonic and sensing technologies. They do not imply that every process available in a national industrial foundry can be reproduced at an academic nanocentre. The scientific advantage lies instead in controlled experimentation, access to sophisticated characterisation and cooperation between materials researchers and device engineers. Work undertaken in such environments can identify mechanisms of failure, assess interfaces and support the development of prototypes before industrial scaling. Shared access also makes expensive equipment available to teams that could not maintain independent laboratories of comparable scope. In the Czech context, this approach represents a substantial form of technological infrastructure distinct from both a university lecture programme and mass commercial production. For emerging computing technologies, this capability can shorten the distance between physical hypotheses and devices suitable for meaningful performance evaluation.

Computer architecture research in Brno demonstrates how a national scientific contribution can emerge without building an entire fabrication industry. At Brno University of Technology, researchers developed methods for hardware–software co-design and for expressing processor architectures in formal description languages. Karel Masařík's work examined the simultaneous design of programmable hardware and software tools for application-specific instruction-set processors. The LISSOM research environment developed associated tools for generating programming and simulation components from architectural descriptions. Its Instruction Set Tools Lissom results were documented by the university in 2007, before the later commercial prominence of configurable processor cores. Such research matters because a processor design is valuable only when software can be compiled, tested and executed against its instruction semantics. Architecture description languages reduce inconsistencies between hardware models, toolchains and simulation environments. They also support systematic exploration of trade-offs among performance, power consumption and implementation cost. The resulting Czech contribution was methodological as well as technological, providing a foundation for subsequent activity in configurable processing systems.

The foundation of Codasip in 2014 illustrates a commercial trajectory emerging from that academic environment. The company traces its origins to research begun by Karel Masařík at Brno University of Technology in the preceding decade. Its work has emphasised processor design tools and configurable intellectual-property cores based on the open Reduced Instruction Set Computer Five (RISC-V) architecture. An instruction set defines the operations visible to software, while a processor implementation determines how those operations are realised in electronic hardware. This distinction enables different manufacturers to develop compatible

implementations with distinct performance, security or energy characteristics. Codasip's activity therefore belongs to the field of processor architecture and design automation rather than being evidence that all associated chips were fabricated in Czech facilities. Participation in the wider RISC-V ecosystem connected expertise originating in Brno with an increasingly international community of hardware and software developers. The company demonstrates a different route to technological relevance from the expansion of a domestic fabrication plant. Its historical importance lies in the conversion of research-based design capability into an internationally oriented engineering business. Its research origins further demonstrate the value of doctoral work whose results later acquire industrial applications not entirely predictable at the outset.

Open instruction-set architectures changed the opportunities available to research teams and specialised hardware developers. The RISC-V approach permits the construction of different processor implementations around a publicly specified set of machine instructions. This does not make every implementation open source, since individual cores, verification environments and commercial support can remain proprietary. For universities, however, the architecture offers a common basis for teaching, experimentation and comparison between different designs. For companies, it creates possibilities to adapt microarchitecture and selected extensions to the needs of embedded control, signal processing or application-specific acceleration. Such flexibility must be balanced against verification costs, software compatibility and the need to maintain effective toolchains. Czech design research was particularly well positioned to contribute to these challenges because it had already investigated the relationship between architectural description and software generation. The broader technological significance lies in making design competence and specialised intellectual property valuable even outside the largest semiconductor manufacturing economies. This is a form of internationalisation through design expertise rather than through ownership of advanced fabrication nodes.

The architecture of computing systems also changed through the growing importance of specialised accelerators. Central processing units remained essential for general control and diverse software workloads, but graphics processing units increasingly handled highly parallel numerical calculations. Field-programmable gate arrays offered another route by allowing electronic logic to be configured for specific tasks after manufacturing. Each architecture exhibits different strengths in memory access, latency, throughput, programmability and energy demand. Consequently, performance comparisons must be based on representative workloads rather than on peak theoretical operation counts alone. Czech computer engineers and researchers engaged with these questions through high-performance computing, embedded systems and accelerator-oriented software. The Karolina supercomputer, installed at IT4Innovations in 2021, illustrates the organisational importance of combining different processing resources for research applications. Yet operating a heterogeneous supercomputer is not the same achievement as inventing the processor designs supplied by international manufacturers. The Czech contribution includes building the environment in which architectures can be evaluated, programmed and applied to scientific problems. The correct engineering choice therefore depends on measured efficiency and software maturity rather than on an assumption that one type of accelerator is always preferable.

Energy efficiency gradually became a central criterion in the evaluation of both processor and system design. A faster calculation may have limited practical value if it requires disproportionate electrical power or cannot be cooled reliably. In embedded devices, energy restrictions affect battery life, thermal stability and the range of environments in which information processing can occur. In supercomputers, the cost of electricity, cooling and facility operation creates pressures to improve the useful work obtained from each unit of energy. Architecture design responds through parallelism, efficient memory hierarchies, specialised instructions and appropriate forms of voltage or frequency management. Semiconductor materials and power-conversion systems influence the same objective from the physical side. This intersection explains why developments in silicon carbide, processor design and accelerator software belong within a common history of emerging computing technologies. Their mechanisms differ, however, and an efficiency gain in power electronics should not be conflated with an algorithmic improvement in information processing. Czech research and industry contributed to this wider transition through selected capabilities rather than through a single unified technological breakthrough.

European integration altered the practical scale at which these research and industrial ambitions could be pursued. The European Chips Act created a framework for supporting design platforms, pilot lines, competence centres and selected advanced manufacturing capabilities. For Czech institutions, participation offered access to partners and facilities that could not economically be replicated within every national research system. The EuroHPC framework similarly linked quantum equipment and classical supercomputing through international procurement and shared infrastructure. Such programmes can strengthen technological resilience when they promote genuine expertise, interoperable systems and sustainable operation. Nevertheless, participation in a European project should not be confused with national ownership of every underlying invention or manufacturing process. The relationship is reciprocal: domestic specialists contribute competence and institutional capacity while gaining access to transnational resources. This form of integration is particularly relevant to high-cost domains such as advanced semiconductors and quantum computers. It allows Czechia to focus its resources on complementary specialisations without claiming complete technological self-sufficiency. European cooperation also exposes participating researchers to shared evaluation standards and to the practical difficulties of coordinating long-lived technical programmes.

The notion of technological sovereignty therefore requires careful interpretation in the Czech setting. It cannot reasonably mean that a medium-sized country produces every semiconductor, operating system, quantum component and specialised industrial machine within its borders. A more defensible understanding concerns the ability to retain critical expertise, evaluate dependencies and participate in trusted international supply networks. Domestic design capacity can improve bargaining power even when manufacturing is located elsewhere, while shared scientific infrastructure can secure access to equipment beyond a national budget. Equally, owning a fabrication facility may provide limited autonomy if essential materials, tools or intellectual property remain externally controlled. The National Semiconductor Strategy and the December 2025 publication of the National Strategy for Quantum Technologies 2026+ acknowledged such interdependencies as matters of policy. These strategies articulated future priorities in research, skills, infrastructure and collaboration rather than proving that the desired

capabilities already existed. Their analytical significance lies in clarifying how economic security, scientific capacity and technological development had become mutually connected. Assessing sovereignty thus requires scrutiny of actual competencies and vulnerabilities, not merely a list of announced national initiatives.

A historical assessment of the period must also recognise substantial limitations in the evidence available for evaluating emerging technologies. Quantum computing benchmarks can change rapidly with improvements in error correction, software and classical comparison methods. Company announcements may describe intended investment rather than completed production, while scientific facility inaugurations may precede unrestricted service availability. Research teams often contribute to international results that cannot be attributed exclusively to one national institution. Patent counts and export statistics may also conceal differences between original design, contract manufacturing and foreign-controlled corporate activity. Consequently, this chapter treats peer-reviewed publications, university records, official strategy documents and dated infrastructure reports as distinct classes of evidence. Their claims are interpreted according to what each source can establish, rather than being combined into a single measure of national excellence. Achievements reported after 2025 are excluded from the historical endpoint even when they clarify the later fate of a project. Such methodological discipline is necessary to understand both the promise and the unfinished character of Czech innovation at the close of the period. Where the available material supports only a prospective benefit, the appropriate scholarly conclusion is to identify the prospect explicitly as conditional.

By the end of 2025, the Czech Republic had assembled a more interconnected environment for emerging computing technologies than existed at the beginning of independence. Research in Olomouc had generated internationally visible results concerning quantum states, measurements and conditional operations, while Prague and other centres cultivated the mathematical foundations of quantum information. Ostrava had gained a newly inaugurated superconducting quantum installation embedded within a multinational computing initiative. Brno had developed a distinctive combination of semiconductor research infrastructure, architecture-design expertise and research-based processor entrepreneurship. The manufacturing tradition at Rožnov remained an important industrial asset, while the national semiconductor strategy sought to expand skills, investment and international integration. These elements did not create an entirely self-contained technological system, nor did they demonstrate that quantum computing had displaced conventional processing. They instead reveal how a country can build recognised capabilities across the difficult boundary between scientific discovery and industrial application. The remaining challenges include long-term financing, research personnel, manufacturing dependence, reliable benchmarking and the conversion of prototypes into sustainable services. Taken together, the Czech experience from 1993 to 2025 shows that technological innovation is cumulative, interdisciplinary and inseparable from the institutions through which knowledge and expertise are preserved.

Part Three

Development of the Czech IT Industry, Digital Entrepreneurship and Information Economy, 1993–2025

The Formation of the Czech Software Industry: Post-Socialist Entrepreneurship, Domestic Innovation and International Market Entry

The formation of the Czech software industry after 1993 was neither a sudden technological discovery nor a straightforward consequence of introducing private ownership. It was a restructuring of the institutions, markets and professional relationships through which computer programmes acquired economic value. Independent Czechia inherited experienced programmers, technical universities, industrial computing departments and a population increasingly interested in personal computers. It also inherited obsolete equipment, uneven access to international products and organisational habits developed under a centrally planned economy. The new entrepreneurial environment permitted software authors to form companies, negotiate with customers and retain commercial rights in their products. Yet market freedom did not automatically provide investment capital, dependable distribution or the managerial skills needed to sustain a technology business. The emerging information technology (IT) sector therefore developed through practical experiments in pricing, product design, support and customer acquisition. Its history must distinguish domestic software products from contract programming, equipment distribution and services performed by foreign-owned subsidiaries. This chapter examines how those activities interacted to create an increasingly diversified Czech software economy between 1993 and 2025.

The human foundations of the new industry were established long before the independent republic appeared. Czechoslovak institutions had cultivated mathematical computing, automatic control, scientific programming and software for enterprise administration despite substantial restrictions on technological imports. Engineers who worked with mainframes, industrial controllers or specialised scientific equipment understood how to solve demanding problems with scarce computing resources. University departments in Prague, Brno and other centres transmitted programming techniques alongside mathematics, electronics and systems engineering. Industrial enterprises employed specialists capable of adapting software to production processes, even where commercial product marketing was unfamiliar. Informal exchanges of programs and technical documentation also helped sustain professional learning outside tightly controlled institutional channels. These traditions did not constitute a competitive private software industry, because intellectual output was largely embedded in public organisations and state enterprises. Nevertheless, they supplied an adaptable workforce when the political and economic conditions of software production changed after 1989. Some established specialists became founders, while younger graduates encountered opportunities that their teachers had seldom enjoyed. The resulting combination of inherited engineering

competence and newly available commercial initiative was a defining resource of the post-socialist transformation.

The political opening initiated by the Velvet Revolution transformed the incentives governing software creation before Czechoslovakia separated into two states. Private enterprise became legally and practically possible on a scale incompatible with the preceding economic system. A programme could now be licensed to customers, upgraded according to demand and financed through revenue rather than through an administrative allocation. Entrepreneurs were able to obtain foreign hardware and operating systems more freely, although affordability remained a serious constraint. Western commercial applications entered the market, placing local developers under immediate pressure to improve compatibility and customer support. The emerging banking and business sectors required software suited to unfamiliar accounting, taxation and commercial practices. Demand was consequently created by institutional transformation as well as by technological enthusiasm. The independent Czech Republic inherited this transition in 1993 rather than beginning it from nothing. Its first software firms operated in markets where the rules of competition, credit and professional contracting were still being established.

One of the earliest commercial opportunities lay in software that made everyday administrative work possible on inexpensive computers. Word processing, bookkeeping, invoicing and stock management were immediately useful to newly established businesses and reorganised public institutions. Software602, operating as a Czech company from 1991, became associated with the widely recognised T602 text editor and the wider adoption of Czech-language computer applications. Such products addressed practical obstacles that imported programs did not always resolve adequately, including local character sets and established document conventions. Their success depended on usability and availability as well as on technical originality. Entrepreneurs learned that reliable installation, printed manuals, updates and telephone assistance could matter as much as the program itself. A locally developed application also offered customers a provider familiar with domestic regulation and business terminology. This relationship encouraged recurring service contracts and incremental product improvements rather than isolated software sales. The early office-software market illustrates how the transformation of working practices generated commercially valuable opportunities for Czech programmers. It also shows why the history of the software sector cannot be reduced to internet start-ups or spectacular technological acquisitions.

Accounting and business-management systems created a second commercial pathway because the new market economy multiplied reporting obligations and organisational complexity. In 1991 Jaroslav Řasa and Petr Vacek established the undertaking originally known as AKTIS to develop software for entrepreneurs, later associated with the ABRA brand. Its products evolved from comparatively simple accounting functions towards broader information systems supporting business operations. The company's documented history records ABRA Gold in the mid-1990s and the emergence of the ABRA G3 enterprise system in 2000. Each transition reflected a wider requirement to connect transactions, inventories, customer records and management reporting within a coherent technical environment. Local tax changes made maintenance an ongoing responsibility, giving providers opportunities to build enduring customer relationships.

Customers also required staff training and data migration when replacing spreadsheets or older standalone applications. These activities supported domestic employment beyond the narrow occupational category of software programming. Such firms proved that specialised local knowledge could sustain product development even when multinational suppliers possessed greater financial resources.

The first Czech software enterprises confronted a market whose distribution infrastructure was still immature. Retail computer shops sold programs alongside hardware, while some developers relied on direct demonstrations and personal contacts with institutional customers. Technical magazines, exhibitions and professional associations provided channels through which prospective users could discover unfamiliar applications. Copy protection and licensing required judgement because unauthorised reproduction was difficult to prevent and strict controls could inconvenience legitimate customers. Many companies therefore treated installation and support as parts of their commercial offering rather than assuming revenue would come from copies alone. Applications designed for Czech language and law possessed an initial advantage within national boundaries but also a smaller potential market. Frequent changes in operating systems forced developers to update interfaces, file formats and hardware requirements. These pressures made commercial survival dependent upon organisational adaptability, not solely upon the quality of initial programming. They also encouraged some firms to target clearly defined professional niches where customer loyalty could offset the relatively modest size of the domestic market. This environment favoured entrepreneurs who understood customer workflows as well as computer technology.

Graphic software demonstrates how local developers could convert specialist technical capabilities into products with broader international potential. Founded in 1993, Zoner initially offered vector-editing software, including Zoner Callisto and Zebra. The company developed Zoner Media Explorer in 1994, anticipating the growing need to organise and edit digital images. Its history records the establishment of an American branch in Georgia in 1999, demonstrating a relatively early attempt to reach customers beyond Central Europe. The company's later emphasis on photographic software reflected changes in consumer imaging and the diffusion of affordable digital cameras. Unlike a consultancy dependent upon individually negotiated projects, a packaged editor can reach customers in several markets through repeated sales of a common code base. Internationalisation nevertheless requires translation, documentation, marketing and understanding of different user expectations. Zoner's evolution illustrates the difficulty of converting a promising application into a sustainable, recognisable product family. It also highlights the strategic value of choosing an identifiable problem rather than competing indiscriminately in every category of software.

Antivirus software became an especially visible example of expertise transferred from research and engineering environments into private enterprise. Pavel Baudiš developed an early antivirus program in 1988 while working with the problem of malicious code, and his subsequent collaboration with Eduard Kučera helped establish the undertaking that became Alwil Software in 1991. The technical task was unusually suitable for international distribution because malicious programs could cross national borders without regard to local accounting rules. Success demanded continuous analysis of threats, rapid updates and reliable relationships with

large populations of users. A small domestic research group could therefore compete through specialised knowledge rather than through the manufacture of computer hardware. Commercial development remained difficult because antivirus programs required long-term maintenance in an adversarial technological environment. The company gradually adjusted its methods of distribution and customer acquisition as internet access became more widespread. In 2001 it introduced a free antivirus product for non-commercial users, strengthening a model in which a broad user community could complement paid services. This example demonstrates how choices about licensing and distribution can alter the international reach of an underlying technical innovation. Detailed developments in cybersecurity companies belong to a later chapter, while their early formation illustrates the entrepreneurial foundations of the wider software sector.

The Czech market also produced companies whose products were intimately linked to changes in commercial computing infrastructure. The enterprise-systems firm LCS, later connected with the HELIOS product family, began in 1990 as a small business with a limited number of founders. Its early economic software developed towards integrated solutions for increasingly complex organisational customers. Such a trajectory depended on understanding business processes and developing relationships with accountants, managers and external implementation partners. For a small software company, the decision to standardise features across clients can be strategically more important than acquiring any single large contract. Standardisation permits a shared product to be updated efficiently while configurable modules respond to sector-specific requirements. At the same time, long implementation cycles may strain cash flow and expose young businesses to risks associated with demanding customers. The difference between a replicable application and an endlessly customised project consequently shaped the economics of software production. Czech companies learned these distinctions through competitive experience rather than by merely imitating foreign enterprise-system vendors.

The internet widened entrepreneurial opportunity by creating new channels through which software services could reach users without conventional retail distribution. The national academic network CESNET began operation in June 1993, while commercial internet provision emerged in 1994. Initially, high access costs and limited connectivity confined many online services to universities, larger businesses and technologically committed users. Nevertheless, the infrastructure made possible a market for websites, internet hosting, electronic mail and the provision of information through browsers. These services required new skills in network administration, database integration and continuously operated software systems. Entrepreneurs faced a different economic problem from that of packaged-software vendors, because an online service could attract visitors before finding a reliable revenue model. Advertising, subscription fees, hosting charges and business commissions offered competing ways to finance the growing internet economy. The gradual commercialisation of connectivity also helped domestic programmers communicate with overseas partners and distribute products electronically. In this sense, network expansion changed both the products Czech companies could sell and the internal organisation of the companies themselves. The internet did not eliminate earlier software markets, but it opened an additional path from local entrepreneurship towards international participation.

Seznam.cz provides a well-documented case of digital entrepreneurship built around the organisation of information for domestic internet users. Ivo Lukačovič launched the service in 1996 with an initial web directory and a relatively small financial commitment. The company's account records the introduction of a full-text search service in 1997 and a free electronic-mail service in 1998. Its early development demonstrates that creating a locally relevant digital product often required careful adaptation to Czech language use and browsing habits. Advertising linked a growing audience to a potential stream of commercial income, although audience size did not guarantee immediate profitability. The enterprise also had to maintain technical infrastructure capable of responding to increasingly frequent requests. Such requirements gradually transformed a small internet initiative into an organisation combining engineering, editorial operations, sales and customer support. The chronology shows how online entrepreneurship differed from selling a program once for installation on an individual computer. A platform had to remain available and useful every day while adapting continuously to competitors and changing technologies.

The establishment of a successful software company was also a problem of access to capital and the allocation of risk. Early founders often relied upon personal savings, revenue from small contracts and the contribution of their own labour rather than specialised venture-financing structures. Commercial banks understandably viewed intangible products and uncertain future sales differently from physical assets that could serve as collateral. Some entrepreneurs therefore financed reusable products through consultancy assignments performed for existing customers. Others sought strategic partners able to offer foreign distribution, technical assistance or a more dependable sales network. The choice between rapid expansion and a slower self-financed trajectory had consequences for ownership and managerial independence. Cash flow could be jeopardised by delayed customer payments, changing exchange rates or the need to maintain several software versions simultaneously. A technically attractive invention might fail commercially because it could not support the costs of implementation and continuing development. These constraints help explain why the Czech software industry developed through diverse business models rather than following a single preferred entrepreneurial formula. They also make later international investment understandable as one possible response to persistent limitations in domestic growth capital.

The emergence of an independent software market required the gradual formation of specialised sales and implementation relationships. A vendor selling enterprise software to a manufacturer could rarely succeed simply by supplying executable files and instructions. Integrators assessed business processes, configured software, transferred data and trained staff to work within a new system. Regional resellers consequently made a national market accessible to firms that lacked their own offices in every industrial centre. Consultants who understood accounting, payroll, production planning or logistics became valuable intermediaries between programmers and customers. The partner model also created potential conflicts over quality, pricing and responsibility for correcting faults after deployment. Successful suppliers developed documentation, certification practices and standard procedures to maintain consistency across implementation partners. This organisational learning made Czech products more scalable and helped distinguish an established software enterprise from a group of capable freelance

developers. The resulting network of vendors and service partners contributed to the professionalisation of the wider domestic information economy.

The professional geography of the industry reflected the distribution of higher education, technical employment and economic opportunity across the Czech Republic. Prague offered proximity to financial institutions, public authorities, corporate headquarters and a concentration of advanced university departments. Brno combined engineering traditions and large student populations with a growing community of specialised software companies. Other regional centres, including Ostrava, Plzeň and Liberec, supported developers working with industrial, technical and business applications. The spatial pattern was uneven because large clients, investment networks and specialist personnel were concentrated in particular urban economies. Yet regional firms could develop competitive positions by focusing on internationally relevant products rather than attempting to reproduce the commercial environment of the capital. Zoner and Y Soft, for example, illustrate the importance of Brno as a source of product-oriented entrepreneurship. Local universities supported recruitment, informal collaboration and the circulation of knowledge, although an educational institution's presence did not guarantee commercial success. The distribution of software activity thus developed through the interaction of local skills, entrepreneurial choice and access to national and international customers. This geographical dimension would become increasingly important as the industry expanded beyond its original domestic client base.

Education contributed more to entrepreneurial development than the simple number of graduates produced in computer-related disciplines. Technical universities taught programming, algorithms, operating systems and electronics, but software businesses also needed knowledge of product management and commercial negotiation. Graduates acquired these additional competencies through start-up experience, private training and work with established international clients. Universities increasingly supported project-based learning, student competitions and contacts with businesses requiring practical software development. These interactions could generate new enterprises, although the intellectual origin of a product and its legal ownership needed to be distinguished carefully. One notable example is Y Soft, established in 2000 by Václav Muchna and Martin di Martini through an initiative linked to Masaryk University in Brno. Its early attention to secure print management shows how a university-connected team could identify a specialised commercial requirement. The challenge was to turn that initial problem-solving capability into a product supported by development, testing, sales and professional management. Such trajectories suggest that entrepreneurship education was most effective when grounded in real technological and organisational demands.

The earliest international markets were often those in which cultural proximity reduced the cost of entering an unfamiliar business environment. Czech developers could approach Slovakia through longstanding professional relationships, partially shared technical traditions and the high mutual intelligibility of the two languages. ABRA's corporate history records the establishment of a Slovak branch in 1994, demonstrating that cross-border expansion could begin soon after Czech independence. Entry into Poland or German-speaking markets generally required more substantial adaptation of documentation, legislation and customer support. International sales also exposed firms to different expectations about contractual responsibility,

quality assurance and the rhythm of software upgrades. Success depended less on the formal existence of a foreign office than on repeatable revenue and the ability to respond to users in another jurisdiction. A product optimised for Czech accounting regulations might require extensive redevelopment abroad, whereas an image editor or security program could travel more easily. These contrasts encouraged entrepreneurs to assess whether their advantage consisted of linguistic proximity, specialised domain expertise or a broadly transferable technical solution. The history of cross-border expansion was therefore a process of learning which forms of knowledge could be exported without losing their commercial value. It also made the distinction between software exports and the provision of local support services increasingly important.

An instructive example of international entrepreneurship originating in a Czech educational setting is the NetBeans development environment. Its documented history identifies a student project called Xelfi, begun in 1996 to create a Java-based integrated development environment. The original team attempted to commercialise its work before obtaining additional entrepreneurial support and formalising a product strategy. The project subsequently attracted the attention of Sun Microsystems, which acquired the associated business in 1999. The acquisition provided access to a much larger international software ecosystem and eventually supported the project's transition towards open-source development. Its historical importance cannot be measured solely by the purchase transaction, because the software became part of the working environment of programmers in many countries. The case illustrates how a technically original university project could generate intellectual property attractive to an established international corporation. It also demonstrates that foreign acquisition does not necessarily terminate the development of a technology originally created in the Czech Republic. Nevertheless, after acquisition, decisions concerning investment and ownership belonged to a different corporate structure, a distinction that must be maintained in assessing national industrial achievement.

The international profile of Prague also attracted software companies whose origins cannot be classified simply as domestic Czech entrepreneurship. JetBrains was founded in 2000 and subsequently developed an important corporate presence and registered headquarters in Prague. Its best-known products include tools for professional software development, with IntelliJ IDEA introduced in 2001 and other development environments appearing in subsequent years. The company illustrates the capacity of Czechia to serve as a base for internationally oriented software activity supported by a multinational workforce. It should not, however, be described as a direct continuation of a pre-1989 Czech state research institute or automatically credited to a uniquely national scientific school. The place of incorporation, residence of employees, origin of founders and geographical location of research are different historical attributes. Large international companies may contribute substantially to the local economy while preserving globally distributed ownership and product development. Their employment and technological influence matter, but so does the accuracy with which national origin is attributed. This distinction prevents a history of the Czech software industry from becoming an indiscriminate catalogue of every familiar technology company with a Prague address. This case also illustrates the importance of separating a company’s registered base from the national origin of its technologies and workforce.

Foreign investment also supported the development of software engineering services delivered by Czech-based teams to international clients. Global corporations could establish local development offices to access engineering expertise, technical universities and comparatively favourable operating conditions. Such offices created employment, introduced new project-management standards and sometimes developed substantial research capabilities. Their commercial relationships nevertheless differed from those of domestic firms licensing products under their own trademarks. A subsidiary might produce highly sophisticated software whose strategic ownership and final marketing were controlled in another country. Conversely, a Czech-owned supplier could subcontract work internationally while maintaining independent responsibility for a narrower specialised product. Both activities contributed to professional experience and demand for skilled labour, but they generated different forms of entrepreneurial autonomy. Evaluating them requires separate consideration of employment, value added, intellectual-property ownership and the ability to determine future technological direction. The growth of internationally connected engineering centres strengthened the Czech ecosystem without rendering the concept of a nationally founded software company irrelevant.

Accession to the European Union (EU) in 2004 altered the legal and commercial setting in which Czech software businesses sought new customers. The European single market offered a more predictable framework for many cross-border transactions and strengthened the circulation of services and specialised personnel. Companies could participate in international procurement and research partnerships while learning to meet more demanding standards of documentation and accountability. European regulatory harmonisation also affected the treatment of intellectual property, consumer relations and later personal-data processing. These changes did not eliminate the importance of national legislation or the practical costs of operating in several languages. Nor did accession automatically transform small Czech providers into globally competitive enterprises. It improved certain framework conditions within which firms still needed convincing products and effective commercial strategies. European research and regional-development programmes could support innovation and infrastructure, although the effectiveness of such support depended upon institutional and entrepreneurial capacities. The post-2004 phase therefore reinforced integration that had already begun through private contracts and international distribution during the 1990s. For software vendors, the practical benefit lay in improved access to customers and partners rather than in an automatic increase in product quality.

Over time, the relationship between software ownership and customer payment underwent substantial change. Enterprise systems added implementation charges, customisation, training and continuing support as distinct sources of income. The spread of reliable connectivity encouraged web-based applications, managed services and subscription arrangements in which software remained under continuous development. Software as a service (SaaS) shifted part of the technical burden from customers to providers, who became responsible for hosting, resilience and coordinated updates. This model promised recurring income but also created regular operational costs and increased exposure to outages or security incidents. Its introduction could reduce the importance of geographical distribution while increasing the significance of trust, privacy and service quality. Firms with established installed products faced

difficult decisions about whether subscriptions would complement or replace perpetual licences. Commercial innovation therefore concerned not only what software could accomplish but also how risks and responsibilities were divided between the producer and the customer. The transition from packaged programs to cloud services was uneven across sectors and should not be portrayed as a simultaneous industry-wide conversion.

Y Soft illustrates how a narrowly defined technical application could become the basis of an internationally active product business. Established in Brno in 2000, the company initially pursued secure access to office printing and related document-management operations. Its historical record identifies an early system enabling user authentication at printers and a 2003 product called SmartQ, a predecessor of YSoft SAFEQ. The underlying commercial opportunity was not an entirely new category of office machinery but the management of existing devices through software and identification technologies. Organisations needed to allocate printing costs, control access and integrate peripheral equipment into their internal procedures. Addressing that problem required cooperation between software developers, electronic-hardware specialists and enterprise customers. Subsequent international growth depended on maintaining a dependable product family while adapting to different devices and organisational requirements. By 2024 the European Investment Bank had signed a financing agreement for research and development activities, illustrating the changed scale at which a company of this origin could operate. This trajectory demonstrates how early problem-oriented entrepreneurship could evolve into more sophisticated technology development without losing its connection to practical customer needs. The example also shows why commercial growth often requires capabilities in enterprise sales and service delivery that were absent from the initial invention.

A durable software industry also depends upon rules clarifying the ownership and permitted use of intellectual creations. Czech copyright legislation, including Act No. 121/2000 Coll., provided a framework within which computer programs could be protected and licensed. Protection of source code should not be confused with a legal monopoly over every idea, algorithm or general functional principle implemented by that code. Developers had to establish rights in employee-created work, third-party libraries, databases, documentation and components obtained from external suppliers. International partnerships introduced additional contractual questions concerning jurisdiction, warranties and the possibility of distributing modified software. Open-source licences offered important alternatives to conventional proprietary arrangements, but they also imposed conditions that organisations needed to understand. Software companies selling to corporate customers increasingly required clear evidence that they possessed the rights necessary to maintain and commercialise their products. These obligations created work for legal advisers and technical managers alongside professional programmers. The institutionalisation of intellectual-property management was therefore part of the transformation from informal software production into a sector capable of negotiating sophisticated international contracts.

The relationship between services and original products remained central as the Czech technology sector grew. Contract software development could provide predictable income when clients financed clearly specified tasks or long-running implementation work. However, a company reliant upon a small number of clients could become vulnerable to their investment

cycles and negotiating power. Developing a reusable product required initial expenditure on design, quality assurance and marketing before sufficient demand was established. A successful product could subsequently reach many customers with a comparatively modest increase in the cost of reproduction. The apparent scalability of software was nevertheless limited by technical support, security obligations and the need to preserve compatibility over time. Some firms adopted hybrid arrangements in which consulting revenue supported product development while product licences created opportunities for expansion. Others specialised deliberately in services and benefited from the growing international demand for experienced engineering teams. Neither model was inherently superior, because profitability and strategic resilience depended upon market conditions, management and the character of the technology offered. The Czech industry's diversity arose partly from the continued coexistence of these different approaches to commercial value creation.

As companies matured, founders also faced choices about outside investment, acquisition and long-term corporate control. Seznam.cz illustrates the use of minority investment to accelerate growth without immediately surrendering the identity of the original business. The company records that Swedish investor Spray Ventures acquired a minority interest in 2000 as the internet service expanded. In 2016, Seznam.cz bought back the shares held by foreign minority investors, demonstrating that international financing and later ownership consolidation could occur within the same corporate history. Other enterprises preferred acquisitions or mergers that broadened their technical capacities and access to markets. These decisions affected the distribution of financial returns, the location of strategic management and opportunities for existing employees. A high acquisition price might demonstrate commercial success while also marking the departure of an independently owned domestic product from the national corporate sector. Retention of domestic ownership, by contrast, did not by itself establish stronger innovation performance or better employment outcomes. A careful history must therefore evaluate financing and ownership changes according to their consequences rather than treat every sale as either an unqualified triumph or a national loss.

The distinction between a small specialist business and a larger technology enterprise becomes visible in the organisation of research and development (R&D). Early founders often combined product design, programming, sales and customer support within a single small team. Growing companies created separate functions for testing, security, design, documentation and strategic product planning. Formal management could improve the reliability of releases, but excessive organisational complexity might slow experimentation and weaken contact with customers. Research expenditure became especially important when companies sought to develop original technological capabilities rather than adapt existing platforms. Collaboration with universities or external laboratories could supply specialised knowledge, although contractual arrangements had to clarify ownership and publication rights. The growth of an innovative firm therefore involved building institutions able to preserve technological competence beyond the direct participation of its founders. Companies that sustained such capabilities were better placed to adjust when operating systems, distribution channels or commercial demand changed. This gradual professionalisation is one reason why surviving firms of the early transition period often appear very different in structure from their original entrepreneurial organisations. It is also a

useful criterion for distinguishing long-term industrial development from short-lived commercial enthusiasm.

Official statistics help establish the economic scale of the sector, but their categories must be interpreted with care. The Czech Statistical Office reports that employment in the wider information and communication technology (ICT) sector was approximately 164,000 in 2017 and 201,000 in 2024. Its published series also records strong growth in the turnover of IT services over the same interval, reflecting the expansion of business activity conducted through digital technologies. Yet the ICT sector includes telecommunications, wholesale and hardware manufacturing as well as programming and related services. These aggregates cannot therefore be treated as precise measurements of domestic software exports or the income of Czech-owned developers. Nor does every person employed by a technology business work directly on original software research. Comparisons across decades also require attention to changes in statistical definitions and the increasing incorporation of digital activities into other industries. The figures nevertheless indicate that computing-related services had become an important component of the national economy by the early 2020s. Quantitative evidence is most useful when paired with company histories, ownership data and evidence of technological products rather than substituted for those forms of analysis.

The export of software is particularly difficult to evaluate solely through visible shipments or conventional industrial statistics. A program may be distributed electronically, incorporated into a foreign company's platform or supplied as part of an ongoing service agreement. Income can arise from licence fees, subscriptions, development contracts, intellectual-property transfers or technical support, and these transactions have different economic implications. Cross-border corporate structures further complicate attribution when a Czech team creates a product marketed and invoiced by a company registered elsewhere. A domestic customer may also generate substantial demand for locally developed software without contributing to direct export revenue. The industry's international contribution must therefore be analysed through multiple indicators rather than reduced to a single national ranking. Relevant evidence includes the geography of customers, the location of engineering work, the contractual ownership of software and the permanence of research teams. Company histories provide useful examples, but they are inevitably selective and may emphasise favourable milestones. Independent statistics and official records remain necessary to assess claims about national competitiveness. This methodological caution is essential when translating entrepreneurial narratives into a history of economic transformation.

The growth of the industry was accompanied by persistent limitations that complicated the scaling of internationally competitive firms. Demand for experienced developers increased competition for specialists in programming, cybersecurity, product architecture and technical management. Small enterprises could struggle to recruit senior staff when larger international employers offered more attractive salaries or access to major projects. In some regions, firms depended upon the continued presence of universities and successful graduates willing to build their careers locally. Access to later-stage finance also mattered when companies attempted expensive international marketing or sustained investment without immediate returns. The European Commission's 2025 assessment identified continuing weaknesses in the digital

transformation of businesses alongside relatively strong digital skills and a dynamic technology environment. These observations indicate that the presence of capable software producers does not automatically ensure the widespread technological modernisation of their potential customers. Firms also faced growing requirements concerning data security, continuity of service and responsible handling of customer information. Addressing such problems required cooperation between entrepreneurs, educational institutions, investors and public authorities rather than reliance upon a single policy instrument.

By the end of 2025, the Czech software economy had evolved far beyond the limited market available to entrepreneurial programmers in the first years after 1989. The sector encompassed locally founded producers of business systems, specialised consumer applications, internet services, security products and tools used by professional developers internationally. It also included internationally owned engineering centres and service companies whose activities contributed skills and value without necessarily creating domestically controlled intellectual property. The transition was shaped by a combination of technical education, market experimentation, product specialisation and the steady improvement of international connections. Early firms such as Software602, ABRA, Zoner and Alwil illustrate distinct paths by which programming competence acquired sustainable commercial expression. Seznam.cz and NetBeans show how the internet and development platforms created alternative routes from local initiatives to much larger technological networks. Y Soft demonstrates the potential of university-linked problem solving to generate a specialist company with a sustained international customer base. Yet these achievements should be interpreted alongside the vulnerabilities of small markets, financing constraints, dependence upon scarce expertise and the complexity of protecting intangible assets. The central historical result was the emergence of an ecosystem in which software became an independently organised field of enterprise, employment and technological investment. Understanding that foundation provides the necessary context for examining the later global market positions of Czech digital companies and their increasingly diverse business models.

Czech Digital Companies and Global Software Markets: Platforms, Enterprise Solutions and Technology Start-ups

The history of Czech digital enterprises between 1993 and 2025 reveals a transformation in which software became an independent source of economic value rather than merely a supporting industrial service. The emergence of commercial internet platforms, enterprise applications and digitally mediated marketplaces opened markets that were scarcely imaginable during the final years of state socialism. Yet these developments followed different commercial trajectories, and the apparent unity of the national information technology industry should not conceal important differences among them. A domestic search platform accumulates advertising demand and local audience knowledge, whereas an enterprise software vendor normally competes through

repeatable specialised functionality and international contractual relationships. A travel marketplace must connect fragmented suppliers and consumers, while a cloud software business seeks recurring revenue from customers whose operations become dependent upon its services. For these reasons, the history of software enterprise formation cannot be reconstructed simply by arranging company valuations or fundraising announcements in chronological order. It must investigate the underlying technological competences, the organisation of product development, the structure of demand and the mechanisms through which firms acquire and retain customers. The origin of the founders, the location of research and engineering teams, the legal domicile of the business and the nationality of investors are related but not interchangeable attributes. This chapter therefore examines Czech entrepreneurial achievements through identifiable products, business models, international partnerships and the institutional conditions that made sustained commercial development possible.

At the beginning of independent statehood, software entrepreneurship inherited a technically educated population but did not inherit a mature venture-capital market or an established network of globally recognised technology companies. Engineers trained in mathematical sciences, telecommunications and computer programming could adapt existing skills to commercial production, but their new businesses still had to discover customers and establish credible distribution. Small domestic markets encouraged specialisation, although the costs of foreign-language marketing and international sales initially placed significant constraints upon ambitious enterprises. The gradual spread of commercial internet access made a different business model available, because an application could reach users without being delivered as a packaged physical product. Advertising-supported platforms, subscription services and transaction intermediaries consequently joined the traditional sale of perpetual software licences and implementation contracts. Universities contributed engineers and methods, but the existence of technically capable graduates did not itself guarantee the organisational knowledge required for successful entrepreneurship. Founders needed to learn product positioning, intellectual-property management, recruitment, sales forecasting and the negotiation of external investment in parallel with technical development. The development of the Czech sector was therefore cumulative, with early software firms, internet portals and corporate service providers establishing commercial experience later reused in other ventures. European Union membership in 2004 broadened the regulatory and market environment, although it did not automatically give Czech suppliers equal access to the distribution channels of much larger competitors. The distinctive feature of the subsequent decades was the increasing ability to combine domestic engineering competence with international customers, partners and sources of growth capital.

Seznam.cz provides a particularly instructive example of a digital business whose initial significance lay in solving a specifically national information problem. Ivo Lukačovič established the service in 1996, when the Czech-language web was developing rapidly but still lacked the organised discovery tools familiar to contemporary internet users. Its original directory assembled links into intelligible categories and thereby reduced the practical difficulty of finding useful pages in a relatively fragmented information environment. The service later added search, electronic mail, maps, information portals and other products, demonstrating that the initial directory had become a platform capable of supporting complementary user activities. The

addition of full-text search in 1997 was technically consequential because Czech accents and character encodings complicated retrieval more than a simple imitation of an English-language indexing system would suggest. By responding to the linguistic behaviour and practical expectations of domestic users, Seznam obtained an advantage that was not reducible to the absolute size of its computational resources. Its advertising model created commercial value from audience attention, but the continuing attractiveness of the platform required investment in search quality and reliable services. The company therefore illustrates how an initially inexpensive entrepreneurial project could develop into an organisation with substantial engineering and infrastructural responsibilities. It also shows that a platform's national specificity may provide a commercial strength even while placing limits upon the direct international transferability of its products.

The continuing development of Seznam.cz demonstrates how platform enterprises expand by connecting previously separate markets rather than merely adding unrelated applications. Search results, business listings, maps, classified advertising and news each create opportunities for users to move between discovery, comparison and action within a shared digital environment. Their integration can reduce acquisition costs because an established audience already recognises the provider and has reasons to return regularly. At the same time, an organisation managing many products must avoid allowing the needs of established services to prevent innovation in newer ones. The commercial importance of Czech-language search was particularly visible when global search businesses were developing economies of scale through international advertising and very large indexing operations. Seznam experimented with external search technologies and subsequently invested again in its own search infrastructure, a sequence documented in its historical account. The decision was not simply a declaration of national independence, since maintaining a search engine required continuing expenditures on crawling, indexing, relevance assessment and processing infrastructure. Ownership of these capabilities nonetheless gave the firm greater control over the ranking system, service integration and strategic development of its principal product. The wider lesson is that domestic digital platforms may sustain competitiveness through locally accumulated data and engineering judgement, while still remaining exposed to global technological and advertising competition. Analysing such businesses therefore requires attention to market structure and continuing investment rather than assuming that early popularity ensures permanent leadership.

The Seznam case also clarifies the differences between platform revenue and the technological assets needed to produce it. A web service can appear free to its everyday users while generating income from advertising customers seeking access to their attention. Advertisers are purchasing visibility, targeting capabilities and measurable outcomes rather than ownership of the underlying search or content systems. Such a two-sided model depends on the presence of sufficient users to attract advertisers and enough commercial resources to finance service improvements. The model can become more resilient when a company develops several complementary products, but it also introduces risks arising from changes in advertising demand and public trust. Integration of editorial content and commercial services creates additional responsibilities concerning transparency and the separation of different organisational functions. The development of Seznam Zprávy from 2016 extended the company's position

towards news production, illustrating a transition from internet intermediation towards a broader digital media business. That expansion cannot be measured solely through software innovation, because journalistic capacity, editorial credibility and distribution relationships become significant elements of the platform. The company consequently exemplifies both the economic potential and the institutional complexity of a Czech-owned digital business operating within an international internet economy.

A contrasting route to international markets was demonstrated by GoodData, founded in 2007 by Roman Staněk, whose earlier entrepreneurial experience included NetBeans and Systinet (GoodData, 2013). Whereas Seznam primarily addressed domestic internet audiences, GoodData pursued business customers requiring analytical information delivered through an accessible software platform. Its origin was closely connected with the movement from locally installed business-intelligence tools towards web-based analytical services managed by a specialised provider. Commercial viability depended upon bringing together data integration, reporting, visualisation and administration in a form that organisational customers could adopt without constructing every technical component themselves. Staněk's previous company-building experience illustrates the accumulation of managerial knowledge across successive enterprises and international acquisitions, rather than a single isolated entrepreneurial breakthrough. The geographic structure of GoodData further complicates simplistic national classification, because commercial leadership and investment relationships were international while significant engineering activity was located in Prague and Brno. This arrangement enabled the company to recruit Czech software specialists while developing customer relationships in markets with larger demand for enterprise analytics. Venture investment supplied resources for product development and international sales, but it also generated expectations concerning measurable growth and competitiveness. GoodData therefore represents a Czech-linked contribution to global software markets whose significance lies in a transnational product organisation and not merely in the founder's nationality. Its experience makes clear why the international positioning of enterprise software vendors must be evaluated through actual engineering activity, customer markets and business architecture.

The technological proposition of a cloud analytics platform is different from the provision of consultancy-based reports assembled individually for each customer. A consultancy sells professional time and bespoke analysis, whereas a reusable software product aims to make its core functions available repeatedly with comparatively limited additional development. GoodData developed its business around shared analytical capabilities that could be incorporated into different organisational workflows and, in some circumstances, embedded within other software products. This product-oriented approach required attention to data modelling, access control, integration interfaces and the reliable operation of analytical services over time. Recurring contractual revenue could support sustained improvement, but the expectation of uninterrupted service also made operational dependability a central part of the commercial promise. Enterprise buyers rarely assess an analytical tool only by the visual attractiveness of a dashboard, because data correctness, security, maintenance and integration with established systems frequently determine long-term usefulness. The business thus occupied a position between the research traditions of statistical information processing and the

operational requirements of commercial information management. Its significance for the Czech digital economy was partly the creation of advanced engineering employment linked to customers beyond domestic borders. It also provided experience in the management of complex cloud software that other firms and individual specialists could carry into subsequent entrepreneurial activity.

The history of GoodData suggests a more general explanation for the internationalisation of Czech enterprise software during the 2000s and 2010s. A relatively small domestic market may be adequate for technical validation but insufficient for a product intended to serve large numbers of multinational corporations. Founders therefore sometimes established commercial headquarters or sales operations abroad while preserving development teams in the Czech Republic. Such arrangements offered access to investors and enterprise purchasing networks, yet they could also complicate the interpretation of where economic value was created and retained. The dependence of a software vendor upon outside funding differs from that of a self-financing domestic portal because sales cycles, implementation costs and revenue recognition can delay the return from product investment. Software-as-a-service business models further expose companies to retention rates, customer acquisition costs and the ability to expand contracts after an initial deployment. These factors are not secondary accounting concerns, since they determine whether technically successful products can maintain commercial independence and finance future research. The Czech contribution to such ventures must accordingly be assessed through technical leadership, employment, ownership arrangements and intellectual-property development rather than through a single corporate address. GoodData illustrates the rewards of combining Czech engineering with international commercial strategy and the tensions inherent in that model. Its trajectory also demonstrates why successful market entry should be distinguished from long-term profitability or technological superiority, which require different kinds of evidence.

Y Soft offers another model in which a specialised operational problem became the basis for sustained international software entrepreneurship. The company emerged in Brno in 2000 from a student initiative associated with Masaryk University, subsequently concentrating on secure printing and the control of office document workflows. Its early products addressed the apparently narrow issue of identifying users and managing the costs of printing and copying across shared devices. The commercial significance of this task arose because large organisations needed administrative control, accountability and consistent operation across heterogeneous printer fleets. By combining server-based software with identification hardware, Y Soft developed a solution requiring competence in both information systems and practical device integration. That technical combination made the company different from suppliers whose product could be distributed entirely as a web application without connections to specialised physical equipment. The progression from SmartQ to YSoft SAFEQ reflected the transformation of a small project into a repeatable product family for institutions with substantial operational demands. The company gradually expanded abroad, indicating that a problem initially discovered in a Czech organisational setting had relevance across national markets. Its history shows how specialised enterprise solutions can build export capacity without depending upon mass consumer recognition or large domestic advertising audiences.

The international expansion of Y Soft depended on a distribution and support model suited to institutional software rather than consumer internet platforms. Enterprise customers often need integration with existing equipment, compatibility across manufacturers and reliable technical assistance throughout a product's operating life. Y Soft therefore expanded through partnerships, international offices, hardware development and successive versions of its SAFEQ platform. Its historical account records overseas expansion, including activities in the United States and Asia, alongside continued engineering and production work in the Czech Republic. These developments required organisational capabilities beyond initial programming, such as manufacturing coordination, certification, service management and technical documentation. The 2015 introduction of subscription-based pricing demonstrated adaptation to a broader enterprise shift from one-off licensing towards more predictable recurring commercial relationships. Subsequent cloud offerings changed the allocation of responsibility between customer infrastructure and vendor-managed services, without eliminating the importance of security or device compatibility. Y Soft's acquisition of the Danish company EveryonePrint in 2022 illustrates the use of corporate acquisition to accelerate entry into an adjacent cloud technology segment. A partnership with the European Investment Bank announced in 2024 further indicated the financing needs associated with continuing research and international development. The enterprise thus developed through the combination of technical specialisation, organisational learning and selective changes in product and ownership strategy.

Kiwi.com demonstrates a substantially different form of digital entrepreneurship grounded in algorithmic coordination across an established global service industry. The enterprise was founded in Brno in 2012 under the name Skypicker by Oliver Dlouhý and Jozef Képesi, and adopted the Kiwi.com brand in 2016. Its central opportunity arose from the fact that travel suppliers did not always provide convenient combined itineraries across carriers that lacked conventional interline agreements. By constructing alternative combinations from available routes and fares, the platform sought to reveal journeys that conventional reservation channels might not present as unified options. This approach required large-scale information retrieval, continually updated prices, search optimisation and interfaces capable of presenting complex alternatives in a form customers could understand. The commercial product consequently depended upon the coordination of data sources and transaction procedures rather than upon operating aircraft or owning the transport infrastructure. Its early growth revealed how a software enterprise located in a medium-sized European city could address a problem extending across the global travel market. Yet the platform also assumed a difficult position between suppliers and passengers, since combinations created by its own software could impose connection and support risks not managed by traditional airline agreements. The distinction between an innovative itinerary-building algorithm and the reliable fulfilment of the resulting customer journey is therefore central to evaluating its achievements.

The commercial design of Kiwi.com illustrates how digital marketplaces can create apparent new supply without changing the physical quantity of the underlying service. Airline seats already existed, but information was fragmented across carriers, distribution platforms and booking arrangements with different rules. Software capable of assembling alternative journeys transformed this fragmented information into additional choices for prospective travellers. The

platform thereby attempted to reduce search costs and exploit opportunities created by differences between supplier networks and customer preferences. Its technological advantage depended upon the speed and quality of data processing, the reliability of itinerary combinations and the customer's confidence in purchasing arrangements. A successful search result was not sufficient by itself, because payment processing, changes, cancellations and passenger communication also shaped the overall transaction. As the company grew, integration with distribution partners and the creation of business-to-business access through its TEQUILA platform extended the market beyond direct consumer booking. This was a shift from one digital interface towards a wider distribution architecture in which third parties could incorporate the company's route-discovery capabilities. Nevertheless, marketplace innovation remained exposed to supplier policies, consumer protection requirements and the operational consequences of events outside the intermediary's direct control. Kiwi.com therefore provides a useful example of both the value created by algorithmic intermediation and its distinctive economic vulnerabilities.

The financing and external development of Kiwi.com show the opportunities and limitations facing a rapidly growing Czech-founded platform in an internationally competitive market. In June 2019, the growth-equity firm General Atlantic announced a strategic investment, while the founders retained significant ownership and continued their management roles. The company had thereby reached a stage at which international capital was expected to support expansion beyond what domestic revenue and early investors could readily finance. The coronavirus pandemic disrupted global travel in 2020, demonstrating how demand shocks can overwhelm the forecasting assumptions on which a specialised digital marketplace relies. Customer service, cancellations and liquidity became inseparable from product performance when travel restrictions interrupted the transactions intermediated through the platform. A further financing arrangement of €100 million in 2022 indicated that investors could still see long-term potential in the business following a period of severe disruption. Such investment should nevertheless be distinguished from realised earnings, since the receipt of new capital does not demonstrate that every aspect of the operating model has become profitable. The case also shows the importance of distinguishing gross transaction value from revenue attributable to the intermediary, because customer expenditure on travel cannot simply be counted as the software firm's sales. Kiwi.com's history is therefore best interpreted through the interaction of algorithmic innovation, travel-industry dependencies and the financial requirements of international scaling.

Rohlik demonstrates how digital commerce can transform a traditional retail activity through the integration of software, physical logistics and customer information. Founded by Tomáš Čupr in 2014, the enterprise began with online grocery delivery in Prague and gradually developed its own warehousing and delivery operations. The technical challenge differed from a conventional online catalogue because groceries are perishable, inventory changes quickly and customers expect narrow delivery windows. Effective operation therefore required software capable of coordinating product availability, warehouse activity, route planning and the communication of reliable delivery promises. The combination of digital interfaces and operational infrastructure meant that the enterprise could not scale solely by adding more servers or online advertisements. Each new service region required physical capacity, trained personnel and sufficiently concentrated

demand to make distribution economically viable. The customer application nevertheless served as the visible interface through which complex warehouse and transport processes could be coordinated. These characteristics position Rohlik within the wider digital economy while distinguishing it from a pure software-as-a-service vendor selling access to standardised functionality. Its history illustrates how Czech digital entrepreneurship increasingly entered sectors in which competitive advantage depended upon bringing software engineering into productive contact with traditional physical operations. The example underscores the need to examine whether technological improvements also generate dependable margins after investment in warehouses and distribution.

Rohlik's expansion created a demanding relationship between software innovation and the economics of fulfilment infrastructure. Inventory systems had to reconcile real-time online demand with goods already assigned to other orders, while distribution algorithms had to accommodate changing travel conditions and customer availability. Introducing automation too rapidly can be costly when order volumes do not justify the equipment or when interfaces between new and existing systems remain unreliable. Conversely, inadequate investment in operational technology can expose a rapidly growing retailer to congestion, poor customer experiences and rising unit costs. The company's subsequent movement into Hungary, Austria, Germany and Romania demonstrated that international scaling involved adapting both the digital product and the logistics organisation to different local markets. A shared technological foundation could support these operations, yet purchasing habits, urban geography, labour markets and local supply chains still influenced commercial performance. For this reason, international expansion should be interpreted neither as the effortless replication of a website nor as proof that every national operation possessed the same economic characteristics. The enterprise illustrates how software can coordinate a transnational service while continuing to depend upon investment in country-specific infrastructure. It also shows why meaningful digital innovation may be found in the integration of familiar technologies into a new operating system rather than in the invention of an isolated algorithm.

The financing of Rohlik demonstrates how the development of a Czech digital company could reach the scale of international private-capital markets. In July 2021, an investment round valued the group at approximately one billion euros, placing it among the businesses commonly described as unicorns. This valuation reflected investors' expectations about prospective growth rather than a direct measurement of annual profit or the market price of a publicly traded company. Later financing rounds included substantial international participation, while the European Bank for Reconstruction and Development became an investor in the enterprise. Such investments supported entry into additional markets, warehouse automation and the development of a more extensive technology and delivery infrastructure. Yet fast growth financed by external capital creates obligations to manage costs and risks that may become more visible when economic conditions change. The significance of the case for Czech entrepreneurship therefore lies both in the ability to attract capital and in the transfer of domestic operational and technological expertise into other European markets. The company cannot be treated simply as a traditional retailer because the customer proposition and fulfilment model depend heavily on internally coordinated digital systems. Neither should it be presented as a pure software export,

since its value creation includes warehouses, goods procurement and last-mile logistics. Private valuation and the productive contribution of software should therefore be considered as separate dimensions of the same entrepreneurial history.

Productboard reflects the emergence of Czech-founded software firms whose products were designed from the outset for international organisational customers. Hubert Palan and Daniel Hejl established the company in 2014 to develop a platform assisting teams with product management and decisions about future development priorities. The underlying commercial problem was not the absence of programming tools but the difficulty of interpreting customer feedback, setting priorities and aligning product work with strategic objectives. Productboard accordingly sought to organise information about user needs and connect that information with the planning of software development. Its proposition depended upon a combination of interface design, collaborative workflows, data organisation and integration with other development systems. The product could be sold across national borders without substantial changes to its basic technical purpose, making it different from services whose success was dependent upon Czech-language consumer habits. International offices and investment partners allowed the enterprise to develop commercial operations near large technology markets while maintaining significant engineering activity in Prague and Brno. Its emergence therefore illustrates the value of identifying a generalisable organisational problem before constructing a specialised recurring-revenue software service. Its significance arises from the interaction between Czech founders, development expertise, transnational customers and internationally organised capital.

The growth of Productboard reveals how venture-backed enterprise software can convert an initial product concept into a company serving organisations at different levels of complexity. Product-management teams differ in size, decision-making procedures and software infrastructure, so the platform needed sufficient adaptability without losing a coherent core. Reusable features and standardised integrations could reduce the cost of serving each additional customer, but support and contractual expectations increased as larger enterprises adopted the product. In February 2022, Productboard announced a funding round of 125 million United States dollars and disclosed a valuation of 1.725 billion dollars. This event demonstrated strong investor expectations but did not independently establish sustainable profits or the long-term durability of the company's market position. Successful scaling also required specialised sales personnel, customer-support capacity and continuing product research, which cannot be replaced by the technical quality of the original software alone. The presence of several major international venture investors showed that Czech-linked businesses could participate in financing networks normally associated with the largest technology markets. At the same time, it underlined the growing importance of governance, investor expectations and strategic accountability in the development of private software enterprises. Productboard thus represents a transition from entrepreneurial software creation towards the management of a complex, internationally financed product organisation. The scale-up also required a governance structure capable of coordinating investment decisions across research, customer success and international sales.

Mews offers another example of a Czech-rooted company developing a specialised cloud platform for customers operating across many countries. Richard Valtr founded the business in 2012 after identifying limitations in conventional hotel-management software while working on a

hospitality project in Prague. Traditional property-management systems frequently relied on locally installed infrastructure and workflows that were difficult to integrate with newer digital services. Mews sought to replace such arrangements with a cloud-oriented operating environment covering reservations, guest services, payments and connected operational processes. Its opportunity lay not only in moving existing records onto remote servers but in rethinking how different hotel functions could be coordinated through a common software platform. Integration with external services became particularly important because hotels rely on distribution channels, payment providers, access systems and specialised operational applications. The business therefore combined software design with the requirements of a highly fragmented international service industry. The example demonstrates how knowledge of operational inefficiencies within one sector can generate a product relevant to customers far beyond the original local environment. Its commercial success nevertheless had to be evaluated through customer retention, service reliability and integration quality rather than the elegance of its original concept alone.

The development of Mews demonstrates the growing importance of acquisition strategies in Czech-linked software internationalisation. A cloud platform serving hospitality companies benefits when it can integrate additional capabilities without forcing customers to maintain separate information systems. Acquiring complementary software providers can accelerate such integration, although it may also create difficulties in bringing different technologies and organisational cultures together. In 2024, Mews announced a funding round of 110 million dollars alongside an account of its recent acquisitions and international expansion. The investment indicated considerable market interest in hospitality technology at a time when many service businesses were modernising their digital operations. However, capital raised during a funding round is not the same as revenue, and a valuation based upon expected growth is not a permanent guarantee of competitive strength. The company's organisational structure was international, but its founders and Prague-based origins made it relevant to an analysis of Czech digital entrepreneurship. The case shows why acquisition can be a deliberate technological strategy when a platform seeks to widen functionality and strengthen customer relationships. It also shows that Czech-linked enterprise software firms had become capable of coordinating complex corporate development beyond national borders by the early 2020s. Its continued development consequently illustrates the importance of balancing integration with stability in platforms that customers use for everyday operations.

The emergence of Keboola illustrates the development of specialised Czech-linked platforms for preparing, moving and transforming organisational data. Founded in 2008, Keboola addressed a problem that became increasingly important as firms accumulated information in different databases, applications and external services. Individual analytical tools cannot produce reliable conclusions when the underlying data remain inconsistent, inaccessible or difficult to combine. A managed data platform can help customers coordinate extraction, transformation and loading processes without constructing every connection and operational procedure independently. This business model gains value through reusable integrations, monitoring tools and arrangements that permit data workflows to be repeated consistently. It also requires continuing attention to access rights, operational costs and the changing interfaces of third-party systems. The

economic significance of the platform arises from reducing the friction between an organisation's existing applications and the analytical functions that rely on their information. International growth is possible because integration problems occur in many economies, even though customers' data governance requirements and technical environments are not identical. Keboola therefore illustrates how commercial software can develop around the maintenance of dependable digital infrastructure rather than around a highly visible consumer application.

Ataccama developed a related but distinct commercial proposition centred on data quality, governance and the management of complex organisational information. Its independent development followed a separation from Adastra in 2007, with products subsequently addressing the need to understand and improve data distributed across enterprise systems. In large institutions, inconsistent definitions, incomplete records and weak information lineage can undermine analysis even when the underlying computing infrastructure is powerful. Commercial solutions therefore need to combine technical discovery, quality checks, metadata management and procedures through which organisations assign responsibility for data. Ataccama's development of its ONE platform reflected the transition from isolated data-quality tools towards more integrated enterprise information management. In June 2022, the company announced an investment of 150 million United States dollars from Bain Capital Tech Opportunities as minority growth capital. This investment reflected the appeal of the wider enterprise data market and offered resources for product development and international commercial expansion. It did not mean that the entire investment represented new scientific research, since growth financing can also support sales, partnerships and organisational capacity. Ataccama exemplifies the evolution of Czech-linked software companies towards specialised global business markets in which the reliability of information becomes an essential component of operational performance. Its history also reinforces the distinction between valuable commercial engineering and original academic discovery, even where the two depend upon similar technical knowledge.

The increasingly diverse Czech business software sector also included applications grounded directly in university research and specialised scientific expertise. Rossum, created by Prague-based founders with backgrounds in artificial intelligence research, addressed the difficult problem of extracting meaningful information from documents used in business administration. Its technology applied machine-learning methods to invoices and other records whose layout and content often make rigid template-based extraction unreliable. Unlike a general-purpose office application, such a product has to combine recognition accuracy with mechanisms for human correction, exception handling and integration into established company workflows. The enterprise attracted major international financing in 2021, illustrating investor interest in transferring machine-learning research into repeatable business services. Yet the success of document automation cannot be judged solely by laboratory accuracy figures, because differences among customers' records may cause significant operational failures. This case therefore highlights the value of continuing evaluation under realistic working conditions and the importance of software interfaces that allow human responsibility to remain visible. It also provides a relatively direct example of scientific training contributing to entrepreneurial capability without implying that every commercial application represents an entirely new scientific theory.

The growth of such ventures expanded the range of industries in which Czech-origin technologies could compete internationally.

The relationships among research institutions, regional innovation organisations and commercial businesses were particularly visible in Brno and South Moravia. The South Moravian Innovation Centre was established in 2003 through cooperation among the city, regional government and universities, with a mission centred upon supporting innovative entrepreneurship (JIC, 2018). Its activities brought together founders, mentors, investors and research organisations that might otherwise have remained only loosely connected. Such intermediary organisations are important because early-stage companies often require help in assessing market demand, protecting intellectual property and presenting products to international customers. The centre’s historical account connects its programmes with the development of ventures including Y Soft, Kiwi.com and companies emerging from local scientific expertise. University participation provided access to skilled researchers and graduates, whereas business mentors contributed knowledge that was rarely supplied through standard engineering curricula. The resulting innovation environment was therefore institutional as well as technological, depending upon sustained relationships and specialised commercial advice. Nevertheless, support programmes should not be credited with creating products independently of founders and research teams, since entrepreneurial responsibility and technical work remained within the businesses. The Brno case illustrates how regional coordination can improve the conditions for internationally competitive digital enterprises without guaranteeing that every supported venture will achieve commercial success. It also helps explain why the Czech digital economy became increasingly polycentric rather than a simple extension of Prague's largest software companies.

The development of venture-capital institutions contributed to the changing opportunities available to Czech software founders during the period under consideration. Early businesses frequently depended upon personal resources, customer revenue or a limited circle of private investors, leaving them vulnerable when product development required sustained expenditure. As specialised investment organisations emerged, founders acquired additional ways to finance engineering teams before their products produced substantial recurring revenue. Prague-based Credo Ventures, active from 2009, exemplified an approach focused on backing founders from Central and Eastern Europe who sought opportunities in international markets. Other private investors, corporate venture programmes and regional initiatives provided funding under different conditions, reflecting a growing but still uneven financial ecosystem. Investment agreements can bring commercial advice and market access, yet they also alter ownership, voting rights and the expectations placed upon founders. The value of capital consequently depends not merely on the amount raised but also on whether the financing model is compatible with the product's development cycle and eventual business economics. European venture financing was especially important for firms whose domestic revenues could not support rapid expansion into markets dominated by better-funded competitors. The history of Czech digital entrepreneurship therefore includes the construction of investor and managerial networks as well as the production of software itself.

Public policy complemented private financing without replacing the commercial discipline required of a sustainable software enterprise. CzechInvest and regional organisations supplied advice, international contacts and programmes intended to improve the conditions in which technology firms could emerge. The Technology Incubation initiative, launched with calls in 2022, sought to provide selected early-stage ventures with financial and non-financial support in strategically relevant fields. Such initiatives could reduce the difficulty of finding mentors and technical partners, particularly for teams emerging from academic environments with limited commercial experience. Nevertheless, public support does not establish that a product has achieved market fit or that customers will continue paying once a grant period has ended. The European Union's research and innovation programmes also offered opportunities to develop knowledge and partnerships, but participation in a research project is different from maintaining a successful product business. Firms need to translate technical results into reliable services, intellectual-property arrangements, pricing models and market-facing organisations capable of meeting customer requirements. Evidence of the effectiveness of support programmes therefore requires attention to business survival, technology development, international sales and the additional activity stimulated by assistance. By 2025, the Czech entrepreneurial environment contained a more developed network of public and private intermediaries than it had possessed during the immediate post-socialist transition. The challenge had shifted from the near absence of support structures towards improving their effectiveness and access across different regions and types of business.

The recruitment and training of engineers formed a further connection between the Czech research system and the international growth of software companies (CzechInvest, n.d.). Universities in Prague, Brno, Ostrava and other centres supplied graduates with expertise in programming, mathematics, data analysis, information systems and related engineering disciplines. Companies also benefited from the circulation of specialists between academic research, multinational technology employers and smaller entrepreneurial teams. Working on a globally distributed product required competencies extending beyond the ability to implement an algorithm or produce functional code. Engineers had to understand testing, security, documentation, software operations, collaboration across time zones and the consequences of product changes for customers. Business growth consequently created demand for product managers, service designers, data specialists, regulatory advisers and professionals able to communicate technical requirements to international buyers. Competition for experienced workers could raise labour costs and expose smaller companies to the attraction of employers with greater financial resources. Conversely, opportunities to work on sophisticated products in Czech cities encouraged the retention of expertise and the return of specialists with international experience. The value of scientific education for entrepreneurship thus resided partly in rigorous technical preparation and partly in its capacity to support continuing learning as commercial technologies evolved.

Digital business models must be evaluated using indicators that correspond to the specific ways in which companies create and recover value. A consumer portal can appear successful through audience reach, yet it remains dependent upon the durability of advertising relationships and the cost of maintaining its services. A subscription-based enterprise vendor must consider customer

retention, recurring revenue and the relationship between acquisition expense and the value of a long-term contract. A travel marketplace needs to separate the gross price of underlying travel services from the income retained for its intermediation, customer support and associated obligations. An online grocery company operates under additional constraints imposed by purchasing, inventory management, warehouse investment and the physical delivery of orders. Capital raised from investors can finance growth in each model, but it should never be interpreted as an operating profit or a direct measure of scientific originality. Likewise, a private-company valuation is an estimate produced through negotiated financing expectations rather than a complete assessment of an enterprise's technological and social contribution. Employment, export sales, the location of intellectual-property development and the persistence of customer relationships offer complementary evidence of economic significance. These distinctions are essential for understanding why companies that belong to the same national digital ecosystem may face radically different prospects despite outwardly similar growth stories. A rigorous history of Czech digital business therefore uses company narratives as material for economic comparison rather than as unquestioned demonstrations of entrepreneurial success.

International investment and corporate acquisition create further difficulties in defining what should count as a Czech technological achievement. A company can originate from a Czech research community while operating through a foreign parent, employing engineers in several countries and licensing intellectual property across different jurisdictions. In such circumstances, the nationality of an investor does not erase the contributions made by the original research team, but the founder's birthplace is insufficient to establish current domestic economic control. Acquisitions may provide distribution capacity, new technologies and financial returns, yet they may also change the location of strategic decision-making and future research priorities. The same distinction applies to international development centres established by foreign corporations in Czechia, where local employment and research can be substantial without the enterprise itself being Czech-owned. The appropriate historical method is therefore to specify which claim is being made: Czech origin, Czech technical participation, local economic impact or ownership by residents and institutions of the country. Each dimension can be relevant, but they answer different questions and require different forms of supporting evidence. This approach avoids turning international entrepreneurship into a competition over exclusive national ownership of inventions that emerged from multinational environments. It also makes it possible to understand Czech companies as contributors to wider European and global production systems without denying their distinctive local intellectual foundations.

By the end of 2025, Czech digital entrepreneurship had developed far beyond the early model of a small software supplier addressing a limited national customer base. The landscape included a mature Czech-language internet platform, specialised enterprise vendors, global travel and hospitality software businesses, data-management companies and technology-intensive online commerce. Firms originating in Prague and Brno had demonstrated several pathways to international markets, including recurring software subscriptions, distribution partnerships, foreign sales operations, acquisitions and venture-financed growth. Their achievements depended upon inherited engineering traditions, the expansion of higher education, the availability of international networks and the gradual development of entrepreneurial support

institutions. At the same time, major differences persisted between scalable software products, marketplaces whose results depended upon outside suppliers and digital services requiring costly physical infrastructure. Challenges concerning skilled labour, growth-stage finance, regulation, competitive concentration and international business management continued to shape the sector. Neither the creation of a successful platform nor a prominent investment announcement alone can explain the strength of a national innovation ecosystem. More important is whether companies can maintain product quality, develop original technical capabilities, serve customers beyond the domestic market and support the formation of new generations of entrepreneurs. The Czech experience between 1993 and 2025 demonstrates that digital development is not a uniform movement from local software to global success but a succession of distinct organisational experiments. Its lasting significance lies in the emergence of enterprises able to translate Czech technological knowledge into internationally traded products while remaining connected, in different ways, to the country's research and educational foundations.

Cybersecurity as a Czech Industrial Specialisation: Antivirus Software, Security Enterprises and Global Technological Competition

The development of cybersecurity as a Czech industrial specialisation illustrates how scientific inheritance, entrepreneurial judgement and changing global demand can combine to create an export-oriented technological sector. Unlike a conventional manufacturing industry, commercial security software is valuable principally because its developers can identify, interpret and prevent threats that constantly change their technical form. The Czech experience is particularly revealing because internationally recognised products emerged from small programming initiatives before the independent republic acquired a developed venture-capital market or extensive digital infrastructure. Avast (originally an abbreviation of AntiVirus Advanced SeT) and AVG (Anti-Virus Guard) became the most visible examples of this transformation, although their histories differed in ownership, distribution, product strategy and relations with international investors. Their success depended upon expertise in reverse engineering, program analysis, software maintenance and the practical understanding of personal-computer vulnerabilities. Yet industrial success cannot be measured only through the number of installations, the value of corporate transactions or the visibility of commercial brands. Effective protection requires technical reliability, continuous updates, responsible handling of information and sufficient trust for users to install software with extensive access to their devices. This chapter therefore examines Czech cybersecurity firms as evolving organisations in which engineering capabilities, commercial strategies and public responsibilities developed together. Its principal chronological focus is 1993–2025, while the late Czechoslovak background explains the unusually strong continuity between pre-independence technical work and subsequent international growth.

The origins of the Prague antivirus enterprise preceded the establishment of the Czech Republic and emerged within a society where personal computing was becoming technically possible but commercially constrained. In 1988, Pavel Baudiš encountered the Vienna computer virus and investigated its behaviour, an experience later described in interviews about the creation of Avast. Such analysis required examining executable instructions and understanding how malicious code altered other programs, rather than treating infection as an ordinary hardware failure. Eduard Kučera became Baudiš's principal entrepreneurial collaborator, bringing organisational competence to a project initially rooted in programming and technical curiosity. Their efforts acquired a more structured form through the Alwil cooperative near the end of state socialism, when conventional private business opportunities remained restricted. The distinction between this cooperative activity and the later incorporated company matters because accounts of a firm's founding may refer to either technological beginnings or legal establishment. After the Velvet Revolution, the partners could reorganise their activities under substantially more favourable conditions for private software production and sales. Alwil Software was established in 1991, creating a clearer legal and commercial setting for the antivirus program that developed into the Avast brand. The foundations of Czech security entrepreneurship thus belonged simultaneously to the technical culture of late Czechoslovakia and to the institutional changes following 1989. The practical history of the enterprise thus began before the legal and economic independence that made its later commercial growth possible.

The experience of Baudiš and Kučera demonstrates why antivirus innovation initially relied upon accumulated programming skill more than expensive laboratories or elaborate corporate structures. Early viruses commonly circulated through removable media and infected executable files, making system integrity checks, signature identification and careful disinfection commercially valuable. The software developer needed to recognise malicious alterations while avoiding damage to legitimate programs or disruption of the user’s work. Such tasks required detailed knowledge of operating systems, file structures, memory behaviour and the practical consequences of programming errors. During the early 1990s, limited domestic purchasing power also constrained the ability of security vendors to finance rapid expansion through a purely national market. Nevertheless, growing access to personal computers created an expanding need for protective software among institutions, firms and households. Security products could be distributed comparatively cheaply once developed, providing a route to sales growth without a proportional increase in manufacturing expenditure. This favourable economics did not remove the recurring cost of researching new threats, testing software and responding to changes in computing platforms. The emerging industry therefore combined low physical reproduction costs with an unusually demanding requirement for continuous technical renewal.

A second major centre of the Czech antivirus industry emerged in Brno through the company Grisoft, founded in 1991 by Jan Gritzbach and Tomáš Hofer. The firm’s flagship antivirus product became known as AVG, and the company developed its route from the Czech market to international users. Brno provided a substantial base of technically educated workers through its universities, engineering community and wider traditions of applied computing. Grisoft initially operated in a business environment where product awareness depended heavily on personal contacts, local distributors and the demonstrable effectiveness of protective tools. As domestic

competition grew, expansion abroad offered a way to reach larger groups of customers without constructing an extensive physical distribution network. The company gradually adopted electronic distribution and English-language marketing, thereby reducing the disadvantages associated with operating from a relatively small national economy. Its corporate development should not be conflated with that of Avast, since the two businesses were independent competitors for most of their histories. Both nevertheless relied upon a central proposition that software produced by Czech development teams could satisfy security needs far beyond the country's borders. Their parallel growth helped establish Prague and Brno as distinctive centres of commercial expertise in computer protection. The different routes to internationalisation would ultimately make their eventual merger a major event in Czech industrial history.

The restructuring of the Czech economy during the 1990s transformed the market for antivirus products in several ways that were not specific to computer security alone. New private firms installed accounting systems, office applications and networked computers, creating a more diverse installed base for developers to protect. Foreign investment encouraged the introduction of international management methods and exposed domestic suppliers to demanding corporate procurement practices. Rapidly evolving software piracy also complicated the commercial environment, since unauthorised distribution could expand brand awareness while undermining revenue from licences. For antivirus developers, an unreliable or obsolete copy presented a particular concern because missed updates could leave the user vulnerable even when the product appeared present. The distinction between initial installation and sustained protection therefore became fundamental to both product design and customer relations. Technical support, automated updating and clear documentation gradually assumed greater importance as domestic software products reached less specialised audiences. This process demanded additional personnel in quality assurance, localisation, documentation and customer service, not only more programmers developing detection engines. The emerging cybersecurity sector thus became a source of diversified professional employment within the wider Czech software economy.

At the technological level, the first generation of commercial antivirus tools was shaped by signature-based detection, which compared suspicious files with recognised patterns associated with malicious programs. These signatures offered considerable precision for previously analysed threats, particularly when carefully designed to distinguish harmful code from harmless applications. However, a signature could not reliably identify an unfamiliar threat merely because the new program was dangerous, creating pressure for faster research and distribution cycles. Heuristic inspection supplemented signatures by seeking structural or behavioural indicators that might reveal malicious intent without requiring an exact match. The methods introduced additional uncertainty because unusual yet legitimate applications could resemble hostile software, producing false positive findings. The engineering challenge was therefore to balance sensitivity against the practical cost of interrupting users, blocking trustworthy programs or destroying valuable files. As operating systems developed, antivirus software also needed to examine memory activity, downloaded content and potentially dangerous interactions between applications. These changing requirements gradually transformed products from occasional scanning utilities into protective services operating

continuously in the background. The underlying scientific principles were international, but their translation into reliable commercial products formed an important part of Czech industrial competence. Reliable performance also became a reputational asset because users often evaluated antivirus quality through the absence of disruption rather than visible defensive action.

The spread of internet connections altered the economics and technical architecture of commercial security software more profoundly than any single innovation in virus detection. A permanent connection gave malicious code additional routes for transmission and made the consequences of infection increasingly dependent upon communication with remote systems. At the same time, internet access allowed vendors to deliver security updates far more frequently than physical distribution through disks or packaged software. A protective product could consequently become a continually maintained service, supported by remote databases and an ongoing relationship between provider and device. The effectiveness of the service depended upon server availability, update integrity and sufficient bandwidth to reach users in diverse network environments. Commercial distribution also shifted towards downloadable installers, online payments and remote customer support, reducing dependence upon national retail partners. For Czech companies this transition was strategically significant because their potential customer base could extend internationally without comparable investment in overseas offices. However, a global customer base generated demands for multilingual interfaces, technical documentation and support across multiple time zones. The internet therefore functioned simultaneously as a new threat environment, an engineering platform and the central infrastructure of international business growth.

Grisoft's introduction of a free antivirus edition around 2000 represented an especially important change in the commercial relationship between software vendors and ordinary users. The company could reach customers unwilling to purchase an unfamiliar security product before experiencing its reliability, thereby lowering a significant barrier to adoption. A free offering also encouraged circulation through download portals and word-of-mouth recommendations, allowing an expanding user community to strengthen the brand's visibility. The business model depended upon converting a smaller proportion of users into paying customers who required additional features, support or business-oriented protection. This approach differed from a conventional time-limited demonstration because the free edition could remain useful without an immediate purchase. Consequently, the company had to manage the economics of serving numerous non-paying installations while sustaining research, updates and technical infrastructure. Corporate filings later described AVG's free-to-paid distribution system as central to its international growth and product strategy. The significance of the model was not that Czech developers invented free software, but that a locally developed security company used it effectively in a global consumer market. By changing the ratio between distribution cost and potential audience, the strategy helped translate engineering expertise into scalable international demand. In this model, widespread free distribution was inseparable from the ability to finance and maintain dependable protection over many subsequent years.

Avast subsequently adopted a comparable approach to free protection, although the exact sequence of product launches requires care because corporate histories often simplify early milestones. The company’s foundation report identifies a free product for non-commercial

household use launched in June 2001, preceding the much broader commercial expansion of later years. Free availability was accompanied by a continuing emphasis on product effectiveness, recognising that a widely distributed antivirus program cannot survive through marketing alone. The strategy created opportunities for recommendations among technically knowledgeable users, who often influenced software choices in families and small organisations. It also provided a foundation for offering paid functionality such as broader security suites, advanced support and protection intended for professional environments. Neither Avast nor AVG could assume that a large free audience would automatically become a profitable customer base without careful management of conversion and operating expenditure. Revenue depended upon product differentiation, perceived risks, distribution agreements and the continuing credibility of claims about protection. The Czech antivirus industry's characteristic innovation therefore lay partly in combining technically demanding products with distribution models adapted to the economics of the internet. This combination allowed firms with modest domestic markets to compete for customers against much larger established software corporations.

International recognition depended upon more than downloading an installation package, because customers needed assurance that protective software would not undermine their computers. Certification, independent product testing and reputation among technical users consequently became important competitive resources for the emerging Czech brands. Antivirus vendors had to demonstrate their ability to identify widespread malware without imposing excessive demands on processor performance or producing disruptive false alarms. Frequent changes in operating systems complicated compatibility, especially when protective tools required unusually deep access to files, processes and memory. Product engineers therefore worked at a difficult boundary between detecting hostile behaviour and preserving the stability of legitimate computing environments. Commercial relationships with distributors and computer manufacturers could extend market reach, but they also created dependence upon external partners and changing contractual terms. Security providers increasingly competed through ease of use, automated configuration and customer confidence as well as through the underlying detection engine. These conditions encouraged the professionalisation of product management, technical marketing and large-scale software testing within Czech development organisations. The result was an industrial model in which research, engineering, usability and commercial distribution were mutually dependent. Recognition acquired through independent evaluations could reinforce the commercial effects of downloadable distribution and free access.

The growth of AVG also illustrates the increasing importance of external investment and ownership change in the international development of Czech security enterprises. After its beginnings as Grisoft, the company attracted private capital from investors who recognised the potential value of its expanding distribution and established product reputation. Benson Oak played an important role in this transition, and subsequent investment introduced additional institutions capable of supporting international expansion. In September 2005, Enterprise Investors announced a substantial investment in Grisoft alongside participation by Intel Capital, giving the company access to wider financial networks. The announcement described an antivirus product already protecting millions of computers and a business with a significant share of sales in the United States. Investment enabled the firm to professionalise management,

enlarge its technological portfolio and pursue geographic growth beyond what retained earnings alone might have supported. At the same time, outside ownership changed decisions concerning strategic direction, governance and the distribution of profits from software developed by Czech teams. The creation of international shareholder structures also complicates simple claims that a company's nationality always coincides with the location of its incorporation. The more informative criterion is the identifiable contribution of Czech founders, engineering teams and research facilities within changing international corporate arrangements.

The internationalisation of AVG was not confined to capital raising but also involved acquisitions and diversification beyond a narrow definition of file-based antivirus scanning. In 2006, the company acquired the anti-spyware business Ewido and incorporated its capabilities into a broader product portfolio addressing different kinds of malicious software. Anti-spyware protection responded to threats involving unauthorised observation, unwanted tracking and software that interfered with ordinary control over a computer. The transition towards suites combining antivirus, anti-spyware and related defences reflected the increasingly varied character of the internet threat environment. Integration presented technical challenges because independently developed components had to share interfaces, updates and system resources without undermining reliability. It also required a coherent product strategy so that users could understand why expanded protection justified paying for functions beyond the free edition. The acquisition demonstrated how a Czech-founded enterprise could use international transactions to complement its internal research and shorten the development of new capabilities. However, buying a technology should not be represented as evidence that every component of the resulting product originated from Czech research. The historical achievement is better described as the capacity to integrate and commercialise specialised technologies within an internationally competitive security platform. Further international growth consequently depended on the management of acquired technologies as well as the creation of new capabilities within the existing Czech teams.

The expanding threat environment of the 2000s and early 2010s forced antivirus companies to reconsider what effective prevention actually required. Criminal activities increasingly involved credential theft, remote control of compromised devices, financial fraud and malicious programs that changed their form to evade inspection. Threats could also arrive through compromised websites, deceptive messages or apparently legitimate software packages rather than through visibly suspicious executable files alone. Detecting them required stronger links between local protection engines, reputation services, network observations and centrally maintained intelligence about emerging attacks. The need for rapid responses increased the importance of automated analysis systems capable of processing large numbers of potentially malicious samples. Researchers and engineers developed combinations of static inspection, controlled execution and behavioural indicators to investigate suspicious programs under repeatable conditions. Such systems had to be reliable enough for industrial operation because a delayed verdict could expose many users before a new protection rule became available. Industrial innovation increasingly involved improving this entire investigative workflow rather than creating an isolated method of recognising one particular virus. Czech companies participated in the

broader international shift from narrowly defined antivirus utilities towards multi-layered consumer and enterprise security services.

Behavioural detection became especially important as attackers learned to modify code without substantially changing the harmful purpose of their programs. A protective system could analyse sequences of operations, suspicious changes to files or attempts to interfere with security tools instead of relying exclusively upon fixed byte patterns. This approach offered opportunities to identify families of threats, although its usefulness depended upon the careful interpretation of legitimate system activity. Some ordinary applications also modify many files, initiate network connections or request powerful privileges, meaning that behaviour alone rarely provides a complete explanation. Industrial detection systems consequently combined multiple forms of evidence and assessed them in relation to context, confidence and the consequences of an incorrect decision. The growing use of large-scale telemetry strengthened the possibility of detecting newly spreading attacks, but also introduced substantial obligations concerning user privacy and consent. Machine-learning methods helped classify complex combinations of features, although their performance depended on representative training examples and continued monitoring for changing attack techniques. The technical contribution of Czech engineering organisations lay in making such systems sufficiently efficient, maintainable and dependable for extremely large numbers of real devices. It would nevertheless be inaccurate to regard any particular commercial classification feature as a wholly Czech scientific invention without supporting technical publications or evidence. An essential technical challenge was to design such systems without treating every unusual user action as evidence of hostile conduct.

Large consumer populations gave the major Czech antivirus brands a distinctive form of observational infrastructure that smaller security vendors could rarely reproduce. When properly governed, information about suspicious files and attacks observed across numerous devices can reveal emerging patterns more quickly than isolated laboratory investigations. The potential benefit increases when the system can correlate related events, identify rapidly spreading campaigns and distribute protective updates automatically. However, the quality of an observation depends upon the context in which it was collected, since legitimate software can resemble malware and malicious activity may remain hidden. A large dataset therefore does not remove the need for human analysis, experimental validation and methods for reducing systematic errors. The associated infrastructure also requires robust storage, access control and procedures that limit exposure of sensitive information about users and their environments. From an economic perspective, global distribution and extensive threat intelligence can reinforce one another, helping an established supplier improve products and sustain market visibility. Yet this positive feedback creates an additional responsibility because companies possess data-processing capabilities far beyond those of ordinary customers. The interaction between scale, detection quality and information governance became one of the defining tensions of the mature Czech cybersecurity industry.

The development of security software for mobile devices widened the technological responsibilities of antivirus companies during the 2010s. Smartphones and tablets introduced application ecosystems, permission systems and patterns of user behaviour that differed substantially from conventional desktop computing. Protection increasingly involved identifying

malicious applications, deceptive permissions, unwanted data collection and threats associated with insecure communications. The restricted access available to ordinary mobile applications also limited the feasibility of reproducing desktop antivirus mechanisms without substantial modification. Software vendors responded by incorporating features such as application assessment, web protection and advice concerning privacy-related risks. Cross-platform operation demanded new release processes because mobile systems and desktop operating systems developed according to different update schedules and security models. A firm that had become internationally successful through personal-computer software therefore had to retain its existing customers while acquiring expertise in unfamiliar platforms. Both Avast and AVG broadened their offerings in this environment, although product availability and features varied over time and between markets. The expansion illustrates how international growth depended upon adaptability rather than permanent reliance on the technical assumptions of the industry's formative decade. As mobile platforms evolved, the relevance of security products depended upon their ability to adapt without unnecessarily extending permissions or collecting excessive data.

The corporate-security market represented a further source of diversification for companies whose principal brands had been built through consumer products. Organisations required centralised management, consistent protection policies, endpoint monitoring and reliable reporting across devices controlled by many different employees. Business customers also expected contractual service levels, administrative tools and support procedures adapted to more complicated operational environments. These requirements encouraged the development of managed security services and products designed for professional information technology administrators. The boundaries between consumer and business markets became less straightforward as home computers connected remotely to corporate networks and employees used personal devices for work. During the coronavirus pandemic, expanding remote access made such questions especially visible, although many relevant technologies had developed earlier. Products originally designed to protect an individual computer were increasingly situated within wider systems of identity management, network access and organisational risk assessment. This market required different forms of customer trust, since a security incident could interrupt an entire enterprise rather than inconvenience a single household. The experience gained by Czech developers across both markets strengthened their technical range but also increased the complexity of corporate product portfolios.

The global capital markets offered another measure of how far Czech antivirus firms had travelled from their initial entrepreneurial settings. In February 2012, AVG Technologies completed an initial public offering and began trading on the New York Stock Exchange, establishing a public market for shares in the company. Its offering documentation described the firm's international customer base, software distribution model and commercial risks in the language of publicly accountable corporate finance. The listing widened visibility among investors but also introduced expectations concerning financial reporting, governance and the predictability of future earnings. These obligations were significant for a company whose earlier expansion had depended strongly upon product adoption and comparatively flexible entrepreneurial management. Shareholder scrutiny could encourage operational discipline while also increasing pressure for acquisitions,

improved margins and demonstrable growth. AVG's listing should not be interpreted as a new scientific discovery, but rather as evidence that a Czech-founded software business had achieved international financial recognition. The event also showed that the development of the Czech digital economy could generate firms capable of participating directly in major foreign securities markets. Such participation changed the meaning of national technological success by separating the location of intellectual production from the legal geography of corporate ownership. The public listing also demonstrated how financial institutions had begun to regard defensive software as a scalable product sector rather than a narrowly local service.

Avast followed a different trajectory towards public-company status, retaining a recognisable connection to its Prague foundations while expanding through international management and investment. In 2010, the Alwil corporate brand was replaced by Avast Software, aligning the company's identity more closely with its globally distributed antivirus products. Professional management became increasingly important as the number of users, employees, subsidiaries and supported platforms expanded beyond the organisational scale of a founder-led business. The company subsequently pursued a major stock-market listing, completing its initial public offering on the London Stock Exchange in May 2018. The London Stock Exchange Group reported a valuation of approximately 3.23 billion United States dollars and total primary and secondary proceeds of about 816.6 million dollars. These figures demonstrated investor interest in an enterprise developed from technical work undertaken in Prague three decades earlier. Nevertheless, stock-market valuation reflects expectations about growth, profitability and competitive conditions, not an independent scientific judgement about every product in the portfolio. The listing also exposed the enterprise to a wider range of international shareholders and the governance requirements attached to publicly traded securities. Avast's experience illustrates how domestic technological capabilities can underpin an internationally owned corporate group without disappearing from its operational structure.

The acquisition of AVG by Avast in 2016 fundamentally altered the competitive relationship between the two leading Czech-founded antivirus brands. An agreement announced in July valued the intended purchase at approximately 1.3 billion United States dollars, with an offer of 25 dollars per AVG share. Avast announced completion of the acquisition of a majority stake on 30 September, with the combined business operating under one organisation from early October. The transaction brought together complementary customer populations, development teams, product portfolios and international distribution relationships. It also reduced direct competition between two enterprises whose origins had demonstrated the possibilities of independent Czech software entrepreneurship. Integration required decisions about overlapping technologies, product branding, customer support and the allocation of engineering responsibilities across different locations. The companies continued to operate recognisable Avast and AVG brands, showing that ownership consolidation did not require the immediate elimination of established product identities. From an industrial perspective, the merger increased scale in a global market where large datasets, brand visibility and continuing research expenditure could create significant competitive advantages. Its historical importance lies in the consolidation of two Czech-origin enterprises into an organisation with greater international reach, rather than in a single new antivirus algorithm. The merger established the basis for further technological

consolidation, while the complexity of integrating distinct research and support cultures remained substantial.

Corporate integration after 2016 also created a larger platform for acquisitions beyond the traditional antivirus market. In July 2017, Avast announced the acquisition of Piriform, the United Kingdom-based developer of the widely used CCleaner optimisation software. The transaction broadened Avast's product portfolio and expanded opportunities to provide related services to users already familiar with free software distribution. Such diversification was commercially logical because consumers increasingly expected security products to accompany other forms of device maintenance and digital privacy protection. However, joining different product organisations also increased the responsibility for security practices across acquired codebases, update systems and development environments. This risk became strikingly visible when a compromised version of CCleaner was distributed in 2017 through the product's legitimate update and installation channels. Avast subsequently published information about the incident and described evidence suggesting that attackers had entered Piriform's environment before the acquisition was completed. The episode demonstrated that security vendors themselves can become targets of sophisticated supply-chain attacks, regardless of the defensive purpose of their products. It also underlined the necessity of auditing acquired software, monitoring release infrastructure and treating secure development processes as part of industrial cybersecurity competence.

The expansion of cybersecurity into broader digital protection reflected changes in consumer behaviour, particularly the growth of connected devices and financial activity online. Users increasingly worried about fraudulent websites, unauthorised tracking, account compromise and personal information appearing in unexpected places. Security companies responded through combinations of browser protection, connection-related safeguards, privacy tools and services intended to reduce everyday exposure to online threats. Such services sometimes relied upon subscription models that offered recurring revenue and encouraged continuing relationships with customers across several devices. The benefits of diversification nevertheless depended upon transparent product descriptions, since consumers might struggle to distinguish essential protection from optional commercial additions. Products addressing privacy and performance could also create conflicts if companies lacked clear rules about collection, processing and use of the information generated through protective software. Competition therefore increasingly concerned the credibility of a broad promise of digital safety rather than narrowly measured rates of recognising infected files. For Czech-founded firms, this transition was both an opportunity to develop additional services and a challenge to preserve the confidence supporting their original antivirus businesses. The resulting industry could no longer be understood solely as a market for software that scans computer disks. Protecting the integrity of updates was consequently as important to public confidence as detecting malware arriving from untrusted external sources.

The controversy surrounding Avast's subsidiary Jumpshot revealed that commercial uses of information could undermine the trust on which security companies depended. Jumpshot received browsing-related information collected through certain Avast and AVG products and supplied derived or collected information for commercial analytics purposes. Avast terminated

Jumpshot's data-collection activities and announced the winding down of its operations in January 2020 after public criticism of these practices. The United States Federal Trade Commission subsequently alleged that the company had misrepresented how browsing information would be shared and that certain data could be re-identified. In June 2024, the Commission finalised an order requiring a payment of 16.5 million dollars and imposing restrictions on the sale or licensing of browsing information for advertising. The order also imposed obligations concerning deletion, notification and the establishment of a comprehensive privacy programme. Avast disputed aspects of the regulator's characterisation while agreeing to resolve the matter under the settlement framework. The case shows why a company's protective function cannot exempt it from independent scrutiny of privacy claims, data governance and consent procedures. It also provides an important qualification to accounts that evaluate the international significance of Czech cybersecurity solely through user numbers or corporate valuations.

The acquisition of Avast by NortonLifeLock in September 2022 marked another decisive transformation in the ownership and organisation of the Czech-founded security sector. The transaction had been announced in 2021 and was completed on 12 September 2022, according to the acquiring company’s corporate reporting. Later that year, NortonLifeLock adopted the name Gen Digital, bringing several established consumer-security brands under a shared corporate identity. The resulting portfolio included Norton, Avast, AVG, Avira and related products, representing a consolidation extending well beyond the original Czech enterprises. The merger gave the enlarged organisation access to international engineering teams, distribution channels and portfolios of complementary defensive technologies. However, it also meant that the historical Czech identity of Avast and AVG could no longer be equated with exclusive Czech ownership or control of corporate strategy. Research capacity retained in Prague and Brno remained relevant to the national digital economy through employment, expertise and professional networks. The distinction between a Czech-founded brand and a fully Czech-controlled company is therefore essential when evaluating technological sovereignty after 2022. Czechia's contribution to the combined enterprise must be assessed through identifiable technological work and human capital rather than through the location of the group's ultimate parent. The eventual outcome demonstrated that security promises must be tested against actual business processes, not judged solely through the defensive functions advertised to users.

The success of Avast and AVG also provided a visible reference point for smaller Czech security enterprises pursuing specialised products rather than mass-market antivirus software. In Prague, Cognitive Security developed techniques using behavioural analysis and artificial intelligence to identify threats in network traffic and organisational environments. Cisco completed the acquisition of this Czech-headquartered company in February 2013, illustrating international demand for specialised local security analytics. The transaction differed from mass-market consumer antivirus mergers because its strategic value lay particularly in expertise and technologies applicable to enterprise networks. Other enterprises focused on problems such as protecting corporate information from accidental disclosure, monitoring communication patterns and securing network connections. Safetica developed products addressing data loss prevention, building on a project begun in Brno in 2007 and later expanding beyond its initial local

market. Whalebone, established in Brno in 2016, developed protective services operating through domain name resolution rather than requiring antivirus installation on every device. GREYCORTEX created network-traffic analysis products intended to reveal anomalous behaviour within organisational and industrial environments. These different specialisations demonstrate that Czech cybersecurity became a broader technological cluster whose capabilities cannot be reduced to two historically dominant antivirus brands.

The diversification of the sector highlights differences between endpoint protection, network-based detection and organisational information governance. An endpoint product operates close to the user's programs and files, creating opportunities for detailed inspection but also requiring careful compatibility with the operating system. Network-based systems examine communication patterns and can identify suspicious activity affecting devices that do not support conventional protective agents. Data loss prevention addresses the movement of sensitive documents and information through authorised as well as unauthorised channels, often involving questions of policy and employee behaviour. Each approach has its own sources of uncertainty, operational demands and possible effects upon privacy or ordinary business activity. The existence of several Czech firms across these categories indicates an increasing depth of engineering specialisation within the national economy. Commercial success nevertheless depends upon more than technical differentiation, including sustainable sales channels, regulatory compliance and the ability to support clients internationally. The capacity to combine specialised security research with effective product management became an important competitive resource for smaller firms seeking to move beyond the domestic market. Their development supports an interpretation of Czech cybersecurity as an ecosystem of distinct capabilities rather than a single uniform branch of software production. These companies occupied markets in which demonstrable reductions in operational uncertainty could matter more than global recognition among household consumers.

Relations between universities, security enterprises and public institutions contributed to the capacity of Czech cybersecurity firms to recruit specialists and maintain technical relevance. Prague and Brno possess universities and research groups concerned with computer science, cryptography, software engineering and analysis of computer networks. Graduates entering commercial security firms brought knowledge of algorithms, program behaviour, statistical inference and the practical design of information systems. Conversely, real security incidents generated problems that could motivate research questions and specialised professional training within the academic sector. Knowledge transfer occurred through employment, informal professional communities, student projects, industrial partnerships and participation in international conferences. However, industrial product development and peer-reviewed research should not be treated as equivalent activities simply because both require advanced computational expertise. A vendor's threat-detection capability may be technologically impressive without constituting a publicly documented original scientific result attributable to a particular university group. The most defensible account recognises specific technical contributions while maintaining the distinction between academic discovery, experimental engineering and commercial application. Within that framework, the cybersecurity sector

demonstrates a productive relationship between national educational traditions and globally oriented software enterprises.

International commercialisation created both opportunities and vulnerabilities for the wider Czech security industry as its products reached foreign households and organisations. Successful vendors gained access to much larger markets than Czech domestic demand could provide, supporting specialised employment and investment in software development. The industry also contributed to the international visibility of Czech engineering through products that users encountered directly in their everyday digital activities. However, foreign-market growth required firms to respond to divergent data-protection rules, consumer expectations, procurement regimes and regional competitive conditions. Concentration in a few globally recognised brands created reputational benefits but also exposed the national sector to the consequences of corporate decisions made outside Czechia. Acquisitions could provide financial returns and access to technologies while reducing local autonomy over research agendas and product strategy. A successful company might maintain substantial development operations in the country even after its shareholder structure and legal headquarters had changed. The historical assessment must therefore consider retained engineering competence and the reproduction of specialist knowledge alongside investment transactions and product sales. By the mid-2020s, Czech cybersecurity's international position reflected both durable technical strengths and increasing incorporation into multinational corporate systems. Export-oriented development therefore offered substantial rewards while making national capabilities increasingly sensitive to the choices of multinational owners and partners.

The period from 1993 to 2025 also changed the professional definition of a security software developer working in the Czech Republic. Early antivirus teams relied strongly on detailed program inspection, low-level knowledge and fast responses to relatively identifiable families of computer viruses. Later organisations needed specialists in distributed systems, data engineering, threat intelligence, user experience, privacy governance and cloud-based product delivery. Machine-learning expertise became relevant to classification tasks, but effective protection continued to require knowledge of operating systems and the behaviour of malicious code. Product teams also had to communicate uncertainty, since no detection system can guarantee that every attack will be recognised before damage occurs. Customer support and incident response increasingly became essential parts of the service rather than peripheral activities after the software had been purchased. The sector's expanding competence profile encouraged interaction with research institutions and international professional networks but also intensified competition for qualified personnel. Industrial sustainability consequently depended upon training, employment conditions and the capacity to retain experienced engineers during successive corporate transformations. The human-capital dimension of Czech cybersecurity was therefore at least as consequential as the visible history of commercial brands and acquisitions.

By the conclusion of 2025, the Czech antivirus industry had become part of a much broader international security market characterised by technical interdependence and concentrated corporate ownership. The growth of Avast and AVG demonstrated that software rooted in Czech technical experience could attain global distribution, attract major investment and influence

commercial models of consumer protection. Their histories also show that technological success is not permanent, since changing threats, operating systems and customer expectations continuously require engineering adaptation. The 2016 merger, the 2018 London listing and the 2022 NortonLifeLock transaction were significant stages in corporate evolution, but none alone explains the scientific substance of cybersecurity. Smaller Czech enterprises broadened the national industrial profile through network analytics, data protection and protective services adapted to diverse operational environments. At the same time, the Jumpshot proceedings and the CCleaner compromise revealed how failures of information governance and software supply-chain security can affect even established vendors. A balanced interpretation must consequently connect enterprise growth with product reliability, ethical responsibility, technological competence and independent evidence of effectiveness. Czechia's enduring contribution lies not in exclusive ownership of a particular global brand, but in the capacity of its research and engineering communities to create internationally useful protective technologies. The resulting history demonstrates both the opportunities and the obligations that arise when a national software industry becomes an influential participant in global digital security. The most credible assessment of the sector combines these economic, technological and ethical dimensions rather than reducing three decades of development to a sequence of mergers.

Video Game Development, Digital Entertainment and Creative Computing Industries

The development of video games in the Czech Republic between 1993 and 2025 reveals an unusually close relationship between software engineering, cultural production and internationally oriented entrepreneurship. Games became a field in which programming, computer graphics, interactive narrative, sound design and commercial distribution had to operate within a single coherent product. Unlike routine software, an interactive game must respond to unpredictable player behaviour while maintaining the consistency of its visual, computational and dramatic environment. This combination of demands made game studios important workplaces for the practical development of simulation, real-time rendering, optimisation and digital artistic techniques. The country’s achievements were not confined to one stylistic tradition, because large military simulations coexisted with historical adventures, transport simulators, experimental narratives and rhythm games. Their production models also differed, ranging from independent teams financed through personal resources to established companies supported by international publishing agreements. The resulting industry gradually acquired the characteristics of a specialised export sector whose products circulated principally through global rather than domestic markets. Understanding its significance therefore requires attention both to individual games and to the technological, organisational and educational capacities sustaining their development. The present section examines these processes without treating commercial popularity alone as sufficient evidence of scientific or engineering originality.

The foundations of Czech game development extend into the final decades of Czechoslovakia, when enthusiasts programmed games for home computers under conditions of restricted access to hardware and software markets. Eight-bit machines encouraged developers to work within severe limitations of memory, processor speed, graphical resolution and storage capacity. Such constraints rewarded ingenious routines, compact data structures and direct knowledge of how computer systems executed instructions. Games also circulated through informal exchanges, clubs and local communities rather than through the comprehensive publishing arrangements familiar in Western markets. After the political changes of 1989, opportunities for private enterprise and international technological exchange altered the possibilities available to these programmers. Nevertheless, the new commercial environment did not eliminate the relevance of their earlier practical experience or the communities through which programming expertise had spread. By 1993, independent Czechia therefore possessed an emerging pool of technically capable developers, although the domestic games business remained comparatively small. Imported equipment, licensed tools and access to foreign publishers gradually made more ambitious production possible during the following years. The historical transition was less an abrupt invention of a national industry than the conversion of dispersed technical creativity into sustainable professional activity. The distinction matters because the creativity of early software communities preceded the formal corporate identities of many later studios.

The establishment of private studios during the 1990s changed how Czech developers financed projects, organised teams and negotiated access to international customers. A commercial game required more than functioning code, since packaging, localisation, quality assurance, publicity and contractual distribution also influenced financial survival. Local purchasing power could not reliably support every ambitious project, making relationships with overseas publishers particularly valuable. Publishers frequently offered advances, distribution infrastructure and access to established commercial channels while retaining influence over schedules and intellectual property. For young Czech firms, such relationships created opportunities for expansion but also exposed them to contractual dependence and considerable delivery risk. Technical specialisation offered one route to differentiation, while distinctive narrative design and artistic identity offered another. Studios consequently learned to transform limited staff and resources into recognisable product qualities rather than simply imitating the largest international competitors. This adaptive process paralleled wider changes in Czech software entrepreneurship but involved especially uncertain production cycles and substantial creative experimentation. The period established production practices that would later support increasingly sophisticated technological projects.

One of the earliest internationally visible outcomes was the tactical action game Hidden & Dangerous, developed by the Brno studio Illusion Softworks and released in 1999. The game combined squad commands, mission planning and three-dimensional environments with an approach that differed from straightforward arcade shooting. Its design demanded coordination among artificial intelligence routines, animation, visibility calculations, collision detection and the behaviour of several controllable characters. The project also illustrated the importance of international publishing relationships to studios operating beyond a comparatively limited Czech consumer market. Illusion Softworks subsequently strengthened its reputation with Mafia: The

City of Lost Heaven, released in 2002, where cinematic storytelling and a detailed urban setting became central elements. Reconstructing an apparently coherent city required technical coordination of driving, character movement, camera systems and changes between scripted events and player-controlled action. These developments demonstrated that Czech teams could undertake complex productions involving both extensive programming and sophisticated audiovisual presentation. Their international significance lies partly in the alternative forms of design they offered within markets otherwise dominated by larger Western publishers. The opportunity to combine tactical challenges with original environments helped the company attract players accustomed to technically demanding software. It would nevertheless be inaccurate to attribute the general invention of these technologies to the Czech studio, since originality lay in particular implementations and their integration.

Bohemia Interactive, established in 1999, developed a different path by emphasising open environments, military simulation and systems that permitted substantial player freedom. Its breakthrough arrived in 2001 with Operation Flashpoint: Cold War Crisis, subsequently associated with the Arma: Cold War Assault name after changes in branding. Instead of organising play around a narrow sequence of scripted encounters, the title placed combat, movement and equipment within a relatively expansive simulated landscape. This approach increased the technical importance of terrain rendering, ballistics, vehicle dynamics, non-player behaviour and coordinated multiplayer interaction. Players could approach tasks through different combinations of movement, command and tactical decision-making, increasing the number of situations software had to handle plausibly (Bohemia Interactive, n.d.). The studio therefore cultivated engineering expertise in systems whose value depended on interactions between components rather than visual effects considered separately. Its work became particularly influential through editing tools that allowed communities to construct additional missions and modify playable content. Such extensibility extended the commercial lifetime of products while creating feedback channels between professional developers and technically experienced players. A substantial share of its technological originality concerned the management of persistent, interactive worlds rather than isolated innovations in graphical appearance.

The Arma series expanded this technological trajectory through successive releases in 2006, 2009 and 2013, combining increasingly complex content with improvements in simulation and online play. Large environments placed sustained pressure on processor scheduling, memory management and the representation of many interacting agents and vehicles. Networked play required mechanisms to synchronise relevant world states among connected computers without allowing communication delays to destroy meaningful interaction. The integration of scripting and modification facilities further complicated testing because community-created scenarios could involve combinations never anticipated by original designers. Experience accumulated through these problems gave the studio knowledge applicable beyond individual game titles. Bohemia Interactive also developed the Real Virtuality technology underlying major parts of its established simulation portfolio. Relationships between games and training applications illustrated how software created for entertainment could become relevant to professional simulation markets. Such transfer should not be misunderstood as identity between a

commercial game and a certified training system, because purposes, validation and technical obligations differ. The important innovation was the cultivation of reusable simulation expertise within a company whose principal audience remained international. This specialisation helped distinguish the Czech studio from competitors focused primarily on cinematic linear experiences.

The survival game DayZ provides another example of the relationship between community experimentation, technical architecture and commercial development. Its origins in modification culture demonstrated that users could create new forms of play from systems originally designed for different purposes. The combination of scarce resources, unpredictable encounters and persistent multiplayer consequences required robust handling of inventory, world states and communication between clients and servers. When developed as an independent title and fully released in 2018, DayZ also became a platform for continuing modifications and extensive live operation. Its significance was not restricted to sales, because the project showed how emergent interaction could become a primary source of player experience. Traditional scripted storytelling was partly replaced by situations produced through the encounters of independent participants within shared constraints. This approach made simulation reliability and online administration essential elements of game design. The development process also highlighted risks associated with extended early access, since changing software must remain accessible to an active audience before final completion. DayZ illustrates the movement from selling a finished technical artefact towards maintaining an evolving digital service with persistent community expectations.

Bohemia Interactive’s introduction of the Enfusion engine in 2021 marked a deliberate effort to renew its technological foundations for a multiplatform future. The company's own description connects the new architecture with improved support for modding, modern graphics and development across several hardware environments. A game engine coordinates numerous systems, including rendering, physics, audio, scripting, content pipelines and network communication. Replacing such a foundation involves unusually high organisational cost because existing tools, expertise and assets must be adapted rather than simply transferred. The 2022 release of Arma Reforger provided a public environment in which the newer technology could be exercised and feedback collected. This relationship between engine development and an accessible game platform allowed technical evolution to occur alongside continuing observation of player behaviour. It also reflected the strategic value of retaining proprietary expertise when commercial objectives require levels of openness or simulation detail unavailable through conventional tools. Nevertheless, ownership of an engine is not automatically superior to licensing one, because the benefits depend on product requirements and long-term maintenance capacity. The Czech example is therefore instructive as an instance of selective technological independence supported by decades of accumulated development experience. Its significance extends to the organisation of engineering work, testing and community production as much as to the engine’s visible output.

SCS Software, founded in 1997 and based in Prague, developed a contrasting but equally durable specialisation in commercial driving simulations. Its international position rested on translating the ordinary processes of freight transport into coherent systems of routes, vehicles, deliveries and business progression. Euro Truck Simulator 2, released in October 2012, became a

particularly prominent example of this approach and continued to develop through subsequent content updates. Creating recognisable roads and vehicles required spatial modelling, texture management, weather effects and a convincing relationship between movement and user control. Underlying economic mechanisms also had to represent cargo contracts, fuel consumption, vehicle upgrades and the expansion of a fictional transport business. These systems were not designed as scientific models of logistics in the strict sense but used selected real-world principles to produce a comprehensible experience. The studio's technical strength was the integration of detailed simulation with accessible pacing and an unusually long product life cycle. By maintaining and extending its games over many years, SCS Software demonstrated the economic value of sustained improvement rather than repeated replacement of entire products. Its development shows how a narrowly defined genre can support globally recognisable intellectual property and substantial specialised employment.

Amanita Design, founded in 2003 by Jakub Dvorský, demonstrates that international competitiveness can also arise from highly individual visual and narrative design. The early Samorost project transformed an experimental artistic concept into a distinctive model of interactive storytelling and digital illustration. Subsequent works such as Machinarium in 2009 and Botanicula in 2012 refined combinations of music, animation, environmental puzzles and surreal imagery. Rather than pursuing visual realism, the studio developed a language of handcrafted objects, peculiar creatures and environments that encourage exploratory attention. Its games often minimise conventional dialogue, allowing gesture, sound and visual arrangement to carry important narrative information across national language boundaries. This aesthetic decision also produces a form of exportability because players need not master extensive Czech-specific text to understand the experience. Technological requirements remain significant, especially in the coordination of animation states, interaction zones, puzzle logic and responsive audio. The relevant originality therefore concerns not the creation of new computing paradigms but the integration of digital technologies into a carefully designed artistic system. Distinctive sound and image together gave the resulting digital worlds identities that were recognisable even without extensive accompanying dialogue. Amanita Design illustrates the commercial potential of cultural distinction within an international market commonly described in terms of graphical performance.

Warhorse Studios represents another model in which technological ambition and historically situated storytelling developed through intensive investment in a large open world. Founded in 2011 by experienced Czech developers including Daniel Vávra and Martin Klíma, the studio concentrated on a role-playing game set in medieval Bohemia. Kingdom Come: Deliverance, released in February 2018, pursued a distinctive combination of historical atmosphere, detailed environments and character development. Its design demanded extensive research into architecture, clothing, equipment, settlement life and historical geography, alongside the computational demands of modern game production. The effort to create a plausible environment required interactions between historical interpretation and the practical limits of animation, artificial intelligence and player accessibility. A convincing medieval world is not equivalent to an authoritative historical reconstruction, because interactivity and dramatic progression necessarily involve selection and invention. Nevertheless, the project created

opportunities for public engagement with particular places and events in Czech history. Its impact illustrates how nationally grounded subject matter can become commercially meaningful when presented through internationally accessible technological forms. The game also showed that Czech studios could compete in a genre requiring years of coordinated work from large multidisciplinary teams.

Warhorse's early business development combined private investment, cooperation with a publisher and a crowdfunding campaign that helped demonstrate audience interest. Crowdfunding could reduce uncertainty about the existence of a committed community, although it did not remove the financial risks of completing a technologically demanding production. The studio's commercial success subsequently attracted the attention of an international corporate group, resulting in its acquisition by THQ Nordic in 2019. The acquisition included intellectual property rights associated with Kingdom Come: Deliverance and demonstrated the economic value that foreign investors attributed to Czech creative assets. The original studio remained located in Prague, illustrating how international ownership does not necessarily erase the local organisation of development expertise. However, the location of engineering work, the nationality of founders and the ultimate ownership of intellectual property must be distinguished in any assessment of national industry. The sequel, Kingdom Come: Deliverance II, released in February 2025, confirmed the continued commercial importance of the historical series. Embracer Group reported sales exceeding one million copies during its first twenty-four hours, providing a documented indicator of international market reach. Corporate changes also altered the relationship between development budgets, intellectual property and organisational autonomy within the studio. That figure describes product reception rather than proving an original discovery in computer science, and it should be interpreted accordingly.

The Czech games industry also contains smaller independent studios whose significance cannot be measured solely against the commercial scale of Bohemia Interactive or Warhorse Studios. Such companies often specialise in narrative puzzles, tactical systems, stylised platform experiences or technically compact experimental projects. Lower budgets may encourage the reuse of established engines, shared development tools and commercial asset pipelines rather than investment in proprietary infrastructure. This dependence can be productive because it allows teams to concentrate scarce resources on mechanics, interaction design and original content. However, licensing costs, platform policies and changes in software ecosystems can create vulnerabilities for projects with limited financial reserves. Small teams also face difficulties in marketing when global storefronts contain very large catalogues of competing titles. Independent success therefore depends partly on recognisable visual identities, communities of interest, festival visibility and relationships with publishers or distributors. The existence of these studios widens the national industry's creative portfolio and helps sustain opportunities for developers working outside the largest production organisations. Their contribution should be understood as diversity of design experimentation rather than as a simple aggregate of product releases.

The rise of Beat Games and the rhythm title Beat Saber introduced an additional dimension through virtual reality and motion-based interaction. Released in 2018, the game linked music and spatial movement within an environment where timing, responsiveness and user comfort

were central requirements. Virtual reality introduces distinctive engineering constraints because delayed visual updates can undermine spatial coherence and cause discomfort even when the underlying gameplay logic remains correct. Beat Saber made these concerns visible through a design whose success depended on precise relationships between audio, hand tracking and graphical feedback. Its strong international reception attracted Facebook, which announced the acquisition of Beat Games in November 2019. The arrangement preserved a Prague-based development operation while placing the studio within a much larger international technology business. This case demonstrates the importance of human–computer interaction as a source of commercial differentiation beyond conventional desktop game design. It also shows that small, highly focused creative teams can generate intellectual property valuable to global platform companies. Responsive virtual environments make the perception of latency and interaction accuracy especially important aspects of player experience. For national analysis, the company's Czech origins and subsequent foreign ownership are complementary historical facts rather than contradictory classifications.

At the level of software engineering, modern video games are among the clearest examples of systems whose complexity emerges from extensive component interaction. A game engine may incorporate rendering, audio, physics, networking, user-interface management and specialised tools for importing artistic assets. Each component can function correctly in isolation while the assembled game still suffers from inconsistent timing, memory exhaustion or unforeseen behavioural interactions. The challenge is therefore not merely to write efficient routines but to establish reliable interfaces and performance constraints across the complete production system. Czech studios producing large simulated worlds encountered these problems particularly directly because many active objects share the same changing environment. Their responses included custom scripting tools, content pipelines, proprietary engines and systematic testing procedures developed for specific production needs. Such work may generate transferable engineering experience even when the source code itself is not publicly released or scientifically documented. It is important to distinguish this practical accumulation of expertise from published theoretical advances subject to academic evaluation. The contribution to the national economy nevertheless remains substantial because experienced engineering teams can sustain complex projects over many years.

Graphics development involves more than increasing polygon counts or producing visually elaborate scenery, since the final image must remain coherent within real-time performance constraints. Artists and programmers coordinate lighting, materials, animation, visibility and asset detail while accommodating differences between hardware configurations. Procedural techniques can reduce repetitive labour by generating or arranging content according to explicit rules, although human supervision remains essential for consistency. Driving simulators illustrate the difficulties of depicting extensive transport networks, whereas military environments demand credible vegetation, terrain and changes in viewing distance. Historically situated games introduce further questions about the appearance of buildings, clothing, objects and inhabited landscapes. Stylised adventures require different solutions because expressive timing and artistic intention may be more important than photorealistic fidelity. The diversity of Czech production therefore offers several models of graphical innovation rather than one uniform

standard of visual progress. Many tools used by national studios were developed internationally, so their local adoption should not automatically be described as a national technological invention. Such differentiated approaches also explain why comparing games solely by graphical realism would overlook important Czech creative achievements. The distinctive achievement frequently lies in the integration of these tools into a coherent aesthetic and interactive experience.

Physical modelling in games demonstrates a similar interaction between engineering approximation and the construction of credible player experience. Vehicle dynamics, character movement, projectiles and collisions can be represented at different levels of detail depending on performance requirements and design priorities. More detailed numerical calculations do not always improve play, especially if the resulting system becomes unpredictable or difficult to control. Transport simulators benefit from recognisable vehicle responses, while tactical games place greater weight on terrain, ballistics and the behaviour of multiple agents. Developers must select which physical processes to approximate, which to simplify and which to replace with designed rules. Real-time execution imposes constraints that distinguish interactive simulations from many research calculations completed without immediate user feedback. Consequently, the term simulation has several meanings and should not be interpreted as a guarantee of scientific validation. Nevertheless, the engineering of credible real-time environments cultivates valuable experience in computational modelling and optimisation. The Czech game sector illustrates how such experience can accumulate in commercially successful projects without implying that every model has research-grade precision.

Artificial intelligence in games also has a distinctive purpose because believable and engaging behaviour may matter more than the formal optimality of an agent's decisions. Non-player characters must respond to navigation constraints, scripted objectives and unexpected player actions within practical computational budgets. Rule-based systems, behaviour trees and planning methods can be combined to produce agents that appear purposeful while remaining compatible with a designer's intended experience. In tactical simulations, credible cooperation and movement become important because the player may observe individual agents across large spaces. In historical narratives, artificial intelligence may instead coordinate routines, conversations and reactions that convey the impression of a living settlement. The computational demands of these systems increase when numerous agents operate simultaneously or when multiplayer users can alter shared conditions. Game development consequently offers demanding tests of software reliability, although success in entertainment does not prove that a method is generalisable to other fields. Connections with academic artificial intelligence are most persuasive when shared methods, publications or collaborative projects can be identified. These agents are often evaluated by whether they contribute to a convincing overall experience rather than by abstract measures of optimisation. The contribution of commercial studios can therefore be recognised without conflating practical game design with fundamental research.

Multiplayer services transformed the organisation of games by requiring continuous administration long after initial release. A networked game depends upon servers, identity management, state replication, security controls and mechanisms for recovering from software failures. Performance problems can affect entire communities even when an individual player's

computer meets the programme’s nominal requirements. Protection against cheating, unauthorised modification and misuse of online services has become a routine development obligation. Games such as Arma and DayZ demonstrate how community servers, modifications and long-running player groups can sustain activity around established technology. At the same time, online infrastructures introduce recurring costs that change the economics of game publishing. Operators must decide how updates are delivered, how data are retained and how users are informed of changes in service conditions. The distinction between a purchased product and a continuously maintained service therefore becomes increasingly difficult to preserve. This transformation links Czech gaming experience with broader trends in cloud computing and internet-based software industries.

Distribution and international marketing changed profoundly when digital storefronts became central to computer-game commerce. Traditional publishing depended heavily on physical production, retail access and national distribution arrangements, often controlled by large intermediaries. Digital platforms reduced several physical barriers to entry and allowed Czech studios to reach international customers without reproducing retail networks in each country. However, discoverability increasingly depended on recommendation systems, platform visibility, promotional timing and player reviews. Smaller teams gained greater access to audiences but still faced intense competition for attention within expanding catalogues. Large studios could exploit recognised franchises, whereas independent developers often relied on distinctive presentation, festivals and community recommendations. Regular updates and downloadable content became important tools for sustaining revenue from established products. Consequently, marketing, localisation and customer communication became integral technical-commercial functions rather than activities occurring only after development. At the same time, digital storefronts create dependence on foreign commercial infrastructures whose decisions local studios cannot directly control. Czech firms adapted to a global marketplace in which the ability to remain visible could be almost as consequential as the initial act of publication.

Industry statistics provide an essential corrective to accounts centred solely on internationally famous games. The Czech Game Developers Association and Creative Europe published a bilingual industry catalogue in 2024 that documented the sector's structure and selected companies. It identified 155 active studios as of the beginning of 2024 and recorded that the overwhelming majority were small enterprises. The publication also reported that more than 98 per cent of industry revenue derived from foreign markets, demonstrating exceptional export orientation. These figures should be interpreted with their reference dates and definitions rather than applied indiscriminately to every year from 1993 to 2025. They do not imply that each studio exports the same proportion of its income or employs a similar number of specialists. The sector includes a small group of comparatively large organisations and numerous teams with far more restricted resources. Differences between later survey estimates also require attention to coverage, accounting periods and the distinction between realised and projected turnover. Nevertheless, industry monitoring establishes that Czech games represent a substantial component of the digital economy rather than a collection of isolated success stories.

Employment within games production combines occupations traditionally associated with technology with professions more familiar from the arts and media industries. Programmers work

alongside animators, environment artists, composers, writers, historians, interface designers, producers and quality-assurance specialists. Their collaboration demands communication across professional vocabularies because artistic decisions frequently have consequences for computational performance and production schedules. A seemingly minor visual change can require new animation, additional testing or modifications to underlying game logic. Likewise, a new technical capability may open creative possibilities that were unavailable when an original narrative was planned. Training programmes therefore need to accommodate both specialised technical depth and an understanding of multidisciplinary project management. The sector's dependence on experienced teams also creates obstacles for new entrants who may possess academic knowledge but lack production experience. Industry organisations have repeatedly identified shortages of qualified personnel as a constraint on expansion. Specialist retention becomes particularly important when companies have invested in production techniques that cannot easily be transferred to new recruits. Educational development must accordingly be assessed not merely through the number of programmes offered but through their capacity to connect students with professional workflows.

Czech universities have contributed to this environment through computer science, computer graphics, interactive media, design and research into games as cultural artefacts. Institutions in Prague and Brno provide different combinations of algorithmic training, software engineering, visual creativity and media analysis. These activities should not be represented as a single nationally unified degree structure because programmes have developed at different times and within different faculties. Professional expertise is also transmitted through studio employment, internships, independent projects and informal developer communities. Game jams and specialist conferences offer environments in which programmers and artists can test ideas within restrictive schedules. Such events can encourage experimentation and professional networking without substituting for systematic academic preparation. Participation in interdisciplinary projects allows students to encounter the practical difficulty of integrating functioning software with designed player experience. The strongest educational linkages emerge when universities retain their research missions while studios provide authentic production problems and practical feedback. This combination can support both the renewal of specialist skills and the expansion of Czech creative industries.

The relationship between games and historical scholarship is particularly visible in projects created with researchers and educational institutions. Attentat 1942, associated with the Czechoslovakia 38–89 initiative and later published through Charles Games, uses survivor testimony and interactive narrative to examine Nazi occupation. Its design places historical interpretation and difficult moral choices at the centre of player experience rather than treating the past as a decorative setting. Documentary material, interviews and contextual explanation create a different educational relationship from the historically inspired adventure worlds of commercial entertainment. Both models can stimulate interest in history, but they should be evaluated through different criteria of evidence and pedagogical intention. Academic scholarship has also examined historical representation in Kingdom Come: Deliverance, illustrating how commercially successful games become objects of independent research. Such inquiry can distinguish plausible reconstruction, selective interpretation and deliberate fictional invention

without denying the artistic value of the resulting game. The Czech experience shows that interactive media can contribute to cultural memory while simultaneously raising questions about authority and representation. Interactive reconstructions also invite players to confront uncertainty rather than treating historical events as a succession of uncontested facts. It also demonstrates possibilities for cooperation among historians, artists, programmers and educators that extend beyond ordinary commercial development.

Creative industries gain additional support from professional associations, cultural institutions and international programmes concerned with the circulation of digital works. Established in 2018, the Czech Game Developers Association undertook the representation of industry interests and the monitoring of sectoral development. Its surveys supplied evidence about company structures, turnover, employment, exports and shortages of qualified workers. Cultural institutions increasingly acknowledged video games as artistic and creative works rather than as a purely technical form of leisure. The Creative Europe programme supported selected European narrative-game projects, including initiatives originating in the Czech Republic. This recognition can widen the range of financing opportunities for studios whose products pursue artistic experimentation or culturally significant topics. However, project funding does not remove dependence on competitive markets, nor does cultural support establish that an individual game will be commercially viable. Public policy must therefore distinguish entrepreneurship, technological innovation, employment and cultural value while recognising the connections among them. The emergence of formal representation marked a further stage in the professional maturation of Czech game development.

Regional geography is another defining feature of the Czech games industry because expertise is concentrated in several cities without being exclusive to the capital. Prague hosts significant development studios, publishing relationships, universities and companies working across a broad range of digital technologies. Brno possesses a particularly important heritage of game production, including early studios and continuing expertise in software and multimedia development. Other regional centres contribute smaller studios, educational initiatives and independent production communities whose activities are less visible in international coverage. The presence of a large employer can strengthen a local labour market by providing experience that later circulates through new enterprises. Conversely, excessive dependence on a few major projects may leave a region vulnerable to cancelled productions or sudden changes in corporate ownership. Remote collaboration and digital distribution can reduce some geographical barriers, although professional networks and specialist facilities remain valuable. A balanced historical account must therefore recognise the influence of metropolitan concentrations while investigating how skills and opportunities spread beyond them. Regional variation should consequently be considered in policies aimed at sustaining new studios and retaining experienced creative workers. The geography of Czech game development reflects both the broader national technological system and the distinct dynamics of creative labour markets.

The relationship between foreign investment and national technological identity becomes more complicated as studios attract international publishers and purchasers. A Czech-founded developer can retain its principal production workforce within the country after ownership passes to a multinational group. Conversely, an overseas-owned studio operating in Czechia may train

local specialists and contribute substantial expertise without possessing Czech-origin intellectual property. Acquisition agreements also vary in how much creative independence, managerial authority and commercial risk remain with the original team. The 2019 purchase of Warhorse Studios and the acquisition of Beat Games by Facebook show two different instances of international corporate interest. These events should not automatically be interpreted as the disappearance of a domestic industry, because production knowledge may remain locally embedded. Neither should foreign acquisition be equated with an unambiguous national success when its consequences for future decision-making are uncertain. Assessment requires attention to investment flows, intellectual property, employment, the location of development and the continuity of original creative leadership. These distinctions are essential for understanding the internationalisation of a technologically specialised national economy.

Economic vulnerability persists despite notable international successes because game development involves uncertain demand and significant expenditure before revenue arrives. Studios may devote years to a project whose commercial prospects remain difficult to establish until publication. A large production can provide sustained employment and develop complex technologies, yet the failure of one major release may threaten the organisation responsible for it. Smaller teams face different risks, including dependence on a single platform, limited advertising budgets and difficulty financing later stages of development. Crowdfunding and early access provide mechanisms for gathering revenue and feedback but may also create unrealistic expectations about schedules or promised features. The global industry has additionally experienced changing investment conditions and restructuring, which can affect national studios through publishers and corporate parent companies. Czech developers therefore balance creativity against financial planning, personnel retention and the disciplined management of production milestones. Their international competitiveness cannot be inferred from a small number of highly visible titles without consideration of projects that did not succeed. Financial resilience often depends on developing several projects or revenue streams without dispersing scarce development expertise too thinly. An analytically mature industrial history must combine accounts of innovation with a realistic treatment of risk and organisational fragility.

Questions of representation and responsibility gained importance as games became persistent services and widely accessible cultural environments. Developers must consider the accessibility of interfaces, the clarity of on-screen information and the needs of players with different physical or sensory capabilities. Online projects face additional concerns involving harassment, moderation, personal data and the security of user accounts. Narrative games may raise questions about cultural representation, historical accuracy and the portrayal of violence or social groups. Revenue systems can also influence design decisions, especially where purchases and repeated engagement become integral commercial objectives. These matters are not separate from technology because platform architectures and interface choices shape what players can do and how they are treated. Research and professional practice increasingly require transparent evaluation of the consequences of such choices. The Czech sector offers cases across a sufficiently broad range of genres to make these questions important, even though answers differ markedly among studios. Sustained reputation in international markets depends

partly on how responsibly companies manage the relationship between software systems and their communities.

By the middle of the 2020s, Czech game development had evolved into an internationally connected industry with diverse engineering and artistic specialisations. Large simulations, detailed historical worlds, independent audiovisual adventures and virtual-reality rhythm games demonstrate that there was no single national design formula. Some organisations invested in proprietary engines and complex online systems, while others used established development platforms to concentrate on novel interaction or visual expression. Across these differences, successful products generally required the integration of technical reliability, coherent design, professional organisation and access to international customers. The sector's strong export profile revealed the capacity of Czech creative and technological work to circulate beyond the limits of domestic demand. Its continued development nevertheless depended on workforce preparation, sustainable investment, fair access to distribution and the survival of younger studios. Industry statistics help measure this transformation, but qualitative analysis remains necessary to distinguish cultural achievement, software engineering and original scientific research. The years 1993–2025 therefore illustrate how a country with inherited programming traditions could create globally visible digital intellectual property through a variety of entrepreneurial paths. The continuing coexistence of innovative small studios and mature international businesses is central to the future resilience of the sector. Czech video games emerge from this history as an important meeting point of information technology, creative culture and international economic participation.

Digital Transformation of Czech Industry: Industrial Software, Semiconductors, Automation and Smart Manufacturing

The digital transformation of Czech manufacturing between 1993 and 2025 was not simply the introduction of computers onto factory floors. It involved changes in how industrial enterprises designed products, coordinated suppliers, controlled machinery, interpreted production data and developed specialised engineering knowledge. The Czech Republic entered independence with substantial capabilities in automotive engineering, machine tools, electrical equipment, metallurgy, glass and other manufacturing activities. Those inherited competences provided opportunities for technological renewal, although their organisational and financial conditions differed sharply from those in established Western European industries. Over the following decades, industrial information technology became increasingly embedded in production equipment and the relationships connecting factories with designers and customers. The resulting history needs to distinguish ordinary computerisation from systems that can monitor processes, modify decisions and connect previously separated production functions. It also needs to distinguish research prototypes, commercially deployed technologies and strategic investments that had not yet entered operation by 2025. For a country strongly integrated into

European manufacturing networks, technological progress frequently arose through cooperation between domestic engineers and international suppliers. The distinctive Czech experience consequently lies in the interaction of industrial continuity, locally developed software, research partnerships and changing positions in global value chains.

Modern industrial computing in the Czech lands inherited practices established well before the independent republic emerged in 1993. Czechoslovak manufacturing had employed numerical machine control, engineering calculation and automated process monitoring within universities, specialist institutes and large state enterprises. Engineers were familiar with the practical value of translating drawings into machine instructions and linking measurements to the regulation of production equipment. Yet equipment availability, access to imported components and organisational incentives constrained the pace at which these methods could spread across enterprises. The economic transformation after 1989 therefore changed both the supply of digital technologies and the reasons companies invested in them. Privatisation and international competition increased pressure to improve delivery reliability, documentation, product quality and compatibility with foreign customers' technical specifications. Some enterprises modernised established factories, while others developed new production facilities under the ownership or influence of multinational industrial groups. The acquisition of foreign machinery could rapidly upgrade an individual workshop without necessarily creating domestic expertise in the underlying control software. The durability of the technological renewal depended on whether acquired machinery also became a platform for locally accumulated engineering and programming experience. Evaluating the transition requires attention to whether Czech teams became active designers and integrators of systems rather than only purchasers of imported equipment.

During the 1990s, computer-aided design and computer-aided manufacturing altered the relationship between engineering offices and industrial workshops. Computer-aided design (CAD) supported the construction and revision of digital product descriptions, while computer-aided manufacturing (CAM) translated appropriate models into production instructions. Their introduction reduced dependence on repeated manual redrawing and enabled more systematic management of variants and technical revisions. Adoption nevertheless required major changes in employee training, documentation standards and the compatibility of equipment bought from different suppliers. An engineering drawing created on one platform could be difficult to integrate with an older machine or a subcontractor's information system. For many manufacturers, the initial economic value of digital tools therefore came from reducing avoidable errors rather than from fully autonomous production. Czech universities and technical institutes provided engineering education that helped enterprises absorb new modelling and programming methods. Private software integrators also emerged to connect imported equipment with local manufacturing practices and customer requirements. The gradual integration of design data and machine operation established conditions for later research in digital production planning and virtual prototypes.

European integration intensified the economic significance of reliable industrial information flows after the Czech Republic joined the European Union in 2004. Automotive producers and their suppliers operated within cross-border supply chains where orders, specifications, quality

documentation and delivery schedules had to remain mutually consistent. Production software consequently became part of industrial competitiveness rather than merely an administrative convenience or an additional engineering tool. Enterprise resource planning (ERP) systems could coordinate purchasing, accounting, inventories and production orders across formerly separate departments. Manufacturing execution systems (MES) addressed more immediate questions about shop-floor activity, the movement of individual orders and the progress of scheduled operations. Product lifecycle management (PLM) systems linked design changes, engineering documentation and configuration information throughout successive stages of product development. These categories describe different functions, and their coexistence did not guarantee that information could move accurately between them. The practical challenge lay in defining responsibilities for shared data, harmonising identifiers and preventing contradictory records from guiding production decisions. A 2025 announcement that Tatra Trucks adopted product lifecycle and low-code platforms provides an additional example of this continuing enterprise-wide integration. Czech manufacturing therefore confronted organisational problems that were inseparable from the apparent technical promise of integrated industrial software.

The industrial economy increasingly demanded precise records of how components were made and how individual machines contributed to their manufacture. Manufacturers of safety-critical automotive parts could not rely solely on final inspection if defects needed to be traced to a particular batch or operation. Digital production records enabled the association of materials, machine settings, inspection results and operator interventions with identifiable products. Such traceability also strengthened communication between suppliers and customers when a quality problem required rapid investigation. However, comprehensive records depended on disciplined data entry, consistent sensors and stable interfaces rather than on software purchases alone. An enterprise could accumulate enormous volumes of measurements without establishing which signals were meaningful for controlling quality or production costs. Industrial data engineering consequently developed as a specialised competence combining manufacturing knowledge, database design and statistical analysis. The transfer of reliable information between workshop equipment and management systems became especially important for companies supplying several European production sites. Over time, these requirements encouraged Czech enterprises to treat information architecture as part of production engineering itself.

The language of Industry 4.0 provided a national policy framework for debates that had already developed within Czech manufacturing practice. A Ministry of Industry and Trade initiative was presented in 2015, and the Czech government approved the Industry 4.0 initiative on 24 August 2016. The initiative addressed investment, standardisation, applied research, education, logistics, security and the potential consequences of increasingly interconnected production. Its significance was not that factories suddenly became intelligent after a government decision but that disparate industrial concerns acquired a shared strategic vocabulary. The programme encouraged cooperation among technical universities, industrial employers, public institutions and suppliers of automation technologies. It also drew attention to the difference between purchasing an isolated robot and reorganising information flows across an entire production process (Ministry of Industry and Trade of the Czech Republic, 2016b). National policy documents could identify priorities and encourage investment, but they could not demonstrate that every

enterprise had implemented the proposed technologies. Realisation depended on the availability of engineers, management capacity, financial resources and technically viable use cases within individual factories. The creation of a shared policy language also made it easier to identify educational and organisational barriers that individual vendors could not resolve. The historical importance of the initiative therefore lies in coordinating expectations while leaving practical performance to be demonstrated by specific industrial projects.

A central characteristic of advanced manufacturing is the connection between physical processes and information systems that can represent their changing states. Cyber-physical systems combine sensors, computational models, communication channels and physical equipment whose activities are mutually related through feedback. The industrial internet of things refers more specifically to connected industrial devices that transmit operational information or support remote monitoring and control. Neither connectivity nor the installation of sensors automatically produces a genuinely intelligent factory capable of adapting to unexpected conditions. Useful industrial decisions require calibrated measurements, knowledge of equipment behaviour and an explicit understanding of how interventions may affect safety. Control loops with strict timing requirements often remain close to machinery, even when larger datasets are transferred to central or cloud computing platforms. Software designers must consequently consider network delay, system availability and the consequences of temporary communication failures. These engineering constraints help explain why Czech industrial digitalisation developed through incremental integration rather than the immediate replacement of established control architectures. They also distinguish the organisation of a working factory from demonstrations that operate under simplified and carefully supervised conditions.

One persistent difficulty concerned the connection of modern software to production equipment acquired in several different technological generations. Large Czech factories often contained reliable machines whose control systems had been designed before contemporary connectivity standards became widespread. Replacing such equipment could be economically unjustified when its mechanical performance remained satisfactory and its replacement would interrupt production. Industrial software specialists therefore developed interfaces that could collect machine status, identify orders and connect selected operations with newer digital services. The resulting architecture frequently combined standardised connections with custom adaptations reflecting the age and technical specifications of existing devices. These integrations had to preserve the safety and predictability of machinery while making operational data usable elsewhere in the enterprise. The most successful modernisation strategy was not always the most technologically elaborate, since maintenance costs and operator competence affected long-term results. Industrial transformation also required clear arrangements concerning who could modify machine settings and who remained responsible for faults after a software update. Responsibility for maintaining such connections became a central question whenever proprietary controllers had to cooperate with newly introduced enterprise software. In this context, software reliability and institutional responsibility became part of the economic evaluation of new production technologies.

An instructive example of locally developed industrial software is the TOS Control system created through cooperation between TOS VARNSDORF and the Czech Technical University in Prague.

The system provides a common interface for machine management while supporting connections between industrial control equipment and wider production information. Its reported functions include unified displays, operational documentation, measurement during machining and access to machine-related information at the workstation. The design also supports extensions intended to improve dimensional accuracy and reduce unnecessary transfers between production and separate measurement facilities. Such integration is technically important for large horizontal boring machines, whose workpieces are costly to reposition and whose machining operations may be prolonged. The university describes how the project moved from development and testing into machines supplied by the industrial partner. By 2020, TOS Control had become a standard component in the manufacturer's new machines, according to the university's account. This case demonstrates that a Czech manufacturer could commercialise software-enabled machine functions alongside the mechanical products for which it was already recognised. Its significance lies in documented technological transfer rather than a general assertion that national machine-tool production had become uniformly digital.

The organisational consequences of the TOS VARNSDORF collaboration extend beyond the immediate functions visible on a machine control panel. The development process created reasons for the manufacturer to maintain software expertise within its own engineering organisation. University specialists and company employees had to reconcile research methods with requirements for stability, serviceability and deployment to customers abroad. Software ownership and revenue-sharing arrangements also became relevant because commercially useful functions emerged from publicly connected research work. The ability to add modules meant that industrial customers could purchase capabilities reflecting particular manufacturing needs rather than replace complete machines. This approach linked the sale of durable equipment with continuing technical support, updates and additional digital functionality. It also changed how the manufacturer could differentiate its products from competitors offering machinery with similar mechanical characteristics. Nevertheless, continuing software maintenance created new costs and responsibilities that could persist throughout a machine's service life. The ability to add digital functions to an established machine design gave manufacturers a route to product improvement without abandoning mechanical expertise. The case illustrates a broader industrial shift from selling isolated equipment towards supplying technologically integrated systems whose value partly resides in software.

Computational modelling developed along a complementary route by enabling engineers to investigate physical production processes before committing resources to full-scale trials. Numerical simulation can represent deformation, thermal behaviour, stresses and other phenomena under assumptions chosen for a particular material or process. Czech engineering research groups have used these methods in forming, heat treatment, materials research and the development of specialised production equipment. COMTES FHT in Dobřany provides an example through its documented work on manufacturing-process optimisation and physical and computational modelling. Digital models can help identify promising process parameters and reduce the number of expensive experiments required to explore a design. However, their predictions depend on material descriptions, boundary conditions and validation against measurements from actual industrial operations. A complex simulation is therefore not

automatically more useful than a simpler model whose accuracy and limitations are well understood. The practical innovation consists in organising modelling, testing and production decisions as parts of one evidence-based engineering process. Such methods strengthened the connection between Czech materials expertise and the computational demands of modern manufacturing.

Digital twins became particularly prominent when enterprises sought to connect virtual representations with changing information from physical assets or products. A static three-dimensional model does not constitute a complete digital twin merely because it resembles an existing machine or factory. A more demanding implementation connects design descriptions, operational measurements, maintenance information and assumptions about system behaviour. Some models are used chiefly for engineering analysis, while others support the comparison of expected and observed conditions during operation. The distinction matters because claims about automatic optimisation require more evidence than the existence of a visualisation or simulated production line. Virtual commissioning, for example, can test sequences of machine operations and control responses before they are executed in a physical installation. This can reduce integration risks where robots, conveyors and processing stations must act together without unsafe interference. Yet digital twins require version control and careful management of discrepancies between the virtual representation and the changing physical system. An engineering simulation has particular economic value when its limitations are communicated clearly enough to influence a real production decision. Their industrial value therefore depends on sustained data governance as much as on advances in graphics, modelling or computational capacity.

The automotive industry provides a particularly revealing environment for examining these possibilities because product complexity and manufacturing volume coexist. Škoda Auto described a Digital Twin initiative within its technical development activities in its 2023 annual report. The initiative aimed to connect data sources across development disciplines and support increasingly comprehensive virtual vehicle development. The company also reported cooperation with the Czech Institute of Informatics, Robotics, and Cybernetics at the Czech Technical University in Prague. One collaborative project used artificial intelligence to anticipate technical bills of materials and vehicle configurations during the early stages of development. The anticipated information could support procurement planning, project calculation and preparation of virtual prototype datasets before every detailed engineering choice had been finalised. This example concerns engineering information and product configuration rather than proof that an entire automotive factory operated autonomously. Its importance is the use of industrial data and research methods to manage complexity at the intersection of design and future production. The project also demonstrates that relationships between multinational automotive organisations and Czech universities can generate identifiable technical work within the national economy.

Artificial intelligence in industrial production has often advanced through narrowly defined tasks rather than through the replacement of complete management structures. Predictive models may identify unusual patterns in measurements, while optimisation methods may suggest feasible production sequences under specified constraints. In engineering design, models

trained on earlier configurations can support estimates of component requirements or help evaluate alternative technical arrangements. Such systems remain dependent on historical data quality and may perform poorly when product designs or operating conditions change substantially. Their results therefore need to be assessed against meaningful industrial baselines rather than against the performance of an untested manual procedure. The technical challenge includes explaining recommendations to engineers who remain accountable for production safety, quality and commercial consequences. Czech research partnerships have become important where industrial companies require expertise in modelling, machine learning and reliable system integration. Successful deployment may be deliberately modest, such as improving an inspection decision or reducing a recurring production delay. These distinctions prevent virtual models used for initial design from being confused with systems continuously updated by operational measurements. The wider significance lies in developing repeatable procedures for validating algorithms under real industrial constraints instead of treating artificial intelligence as an independent guarantee of productivity.

Automation in Czech automotive production must also be understood through the organisation of suppliers, assembly operations and logistics. Industrial robots can undertake repetitive handling, welding or positioning tasks, but they do not eliminate the need for process engineering and careful maintenance. Different production operations involve different levels of flexibility, with some benefiting from fixed automation and others requiring adaptable tools or human judgement. The economic rationale for automation consequently varies with production volume, labour availability, component variety and the cost of unplanned stoppages. Automated material transport can improve consistency when plant layouts, safety systems and inventory information are coordinated effectively. Nevertheless, isolated automation may move a bottleneck to another workstation rather than improve the performance of the complete factory. This systems perspective has particular relevance in Czechia because automotive production connects large manufacturers with numerous smaller subcontractors. Technological choices made by leading vehicle producers can influence documentation standards and investment priorities throughout their supplier networks. Industrial digitalisation thus propagates through contractual relationships as well as through independent decisions made within individual Czech factories.

Smart logistics has enlarged the scope of industrial information systems beyond the immediate manufacture of a component. A factory must often coordinate deliveries from numerous suppliers while managing the movement of unfinished products between processing and assembly operations. Digital scheduling can associate material requirements with production orders and provide earlier warnings when an essential component is delayed. Location tracking and automated storage technologies can improve visibility, but their contribution depends on the correctness of inventory records. Unreliable records may instead lead an automated system to issue plausible but ineffective instructions at greater speed than a manual process. Industrial logistics therefore benefits from common identifiers, dependable communication and procedures for managing exceptions when ordinary workflows fail. Enterprises connected to international automotive value chains have a strong interest in exchanging accurate information with organisations beyond their own boundaries. These relationships make interoperability a commercial requirement even when manufacturers use different enterprise software products.

Such examples also reveal that the most useful applications often support human engineers instead of attempting to remove them from industrial decisions. In the Czech setting, the digital factory increasingly became a network of coordinated activities rather than a geographically isolated production hall.

The monitoring of machine condition offers another route through which Czech industrial research can produce measurable operational benefits. Sensors may reveal vibrations, temperature changes or other signals associated with tool wear, mechanical deterioration or abnormal operating conditions. Data analysis can help maintenance teams recognise changes earlier than would be possible through fixed inspection intervals alone. However, an unusual measurement is not equivalent to a verified prediction of failure, and erroneous alerts can interrupt production unnecessarily. Useful predictive maintenance therefore requires engineering interpretation, recorded maintenance outcomes and careful attention to the consequences of missed faults. The Czech public research database documents a 2021 machine-tool prototype associated with TOS VARNSDORF that combined machine monitoring and prediction using control data, supplementary sensors and virtual models. This result is more specific than a broad claim that predictive maintenance had become routine across the country's factories. It shows how machine builders and researchers could embed condition-oriented software in actual industrial equipment. The achievement demonstrates the convergence of traditional machine engineering with information systems whose outputs support decisions throughout a product's working life.

Machine vision and automated quality assessment have become relevant wherever complex industrial products require consistent inspection under controlled conditions. Cameras and image-processing algorithms can identify missing components, inspect surfaces or support the positioning of robotic systems during production. Such tasks bring computer science into direct contact with illumination, optics, mechanical tolerances and the characteristics of manufactured materials. A model trained to recognise defects in one product may not transfer reliably to another product with different surface properties or manufacturing conditions. Consequently, quality assurance requires traceable reference samples and clear rules for assessing false alarms as well as missed defects. Industrial acceptance should be measured through practical error costs and production throughput rather than through laboratory classification accuracy alone. Research laboratories can offer controlled facilities in which sensing, robotic manipulation and inspection methods are tested before expensive factory deployment. This role has become increasingly important in the Czech research ecosystem because small manufacturers often cannot afford independent experimentation with every emerging technology. The integration of transport data with manufacturing plans is particularly important when suppliers operate under tightly specified delivery windows. Successful technology transfer therefore depends on experimental designs that reflect industrial variation instead of merely producing attractive demonstrations.

Industrial connectivity creates obligations for operational cybersecurity that differ from the protection of ordinary office information systems. A disruption to a machine controller can cause physical damage or endanger workers even when no commercially sensitive data are stolen. Industrial systems must therefore distinguish the confidentiality of information from the

availability and integrity of time-critical operations. Connecting long-lived machinery to external services can create vulnerabilities where equipment was not originally designed for continuous network access. Manufacturers need appropriate separation of networks, controlled maintenance access, tested recovery procedures and clear responsibility for software changes. These requirements can conflict with demands for convenient remote monitoring or rapid installation of new digital functions. Czech policy documents have accordingly treated security and standardisation as integral aspects of industrial transformation rather than optional additions. The more closely factories exchange information with suppliers and research partners, the more carefully they must govern permissions and shared technical data. Industrial modernisation succeeds only when new connectivity is accompanied by credible methods for protecting the continuity and safety of production.

Institutional cooperation became increasingly important because no single Czech enterprise could independently master every technology associated with advanced manufacturing. The Research and Innovation Centre on Advanced Industrial Production (RICAIP) provides a prominent example of this networked approach. Its partners include the Czech Institute of Informatics, Robotics, and Cybernetics, the Central European Institute of Technology at Brno University of Technology, and two German research organisations. The initiative connects test facilities in Prague, Brno and Saarbrücken in a distributed research environment concerned with industrial robotics and artificial intelligence. European project documentation describes a partnership intended to strengthen research capabilities while enabling industrial experimentation across institutions. The project began in 2019, with its funded implementation period extending beyond the 2025 endpoint of this historical study. It should therefore be characterised as an infrastructure under development during the period rather than an entirely completed programme in every planned dimension. The distributed model enables comparison of technologies in distinct experimental environments and creates opportunities for enterprises to collaborate without building equivalent facilities themselves. Testing under variable lighting and changing product geometries is therefore necessary before a laboratory vision method is treated as a dependable industrial service. Its scientific value lies in connecting research, testing, technical training and industrial requirements through an identifiable international partnership.

The industrial testbed at the Czech Institute of Informatics, Robotics, and Cybernetics in Prague illustrates the practical purpose of such research infrastructure. Its experimental manufacturing arrangements bring together robots, machine tools, handling systems and software for production planning and process observation. Unlike a standard factory, the facility is designed to permit repeated modification of arrangements without exposing a commercial production line to the same degree of risk. Researchers can test how changes in one operation influence material movements, scheduling and the behaviour of connected equipment. Companies can also examine technical concepts before deciding whether particular investments are justified by their own production requirements. The National Centre for Industry 4.0 and an initial stage of the Prague testbed were formally launched in September 2017. Founding partners included technical universities, industrial employers and regional innovation organisations, demonstrating a deliberate attempt to connect different kinds of expertise. The centre's contribution should be evaluated through experiments, demonstrations and technology-transfer relationships rather

than through the number of technologies visible in its laboratory. This distinction is essential because the successful operation of a testbed does not establish the economic feasibility of the same configuration in every industrial setting.

Brno contributes another component of the Czech industrial research system through its technical universities, engineering companies and specialised experimental facilities. The Central European Institute of Technology at Brno University of Technology participates in RICAIP alongside the Prague and German partners. Its position connects research in advanced manufacturing with the region's established expertise in electronics, mechanical engineering and materials technologies. Brno's industrial ecosystem also includes companies concerned with machine control, software integration, precision instruments and semiconductor-related activities. Such regional proximity can facilitate collaboration when a research question requires engineers, programmers and physical-production specialists to work on the same problem. However, institutional presence alone does not demonstrate that an entire local manufacturing sector has achieved a uniform level of digital maturity. The more meaningful question is how experimental knowledge passes into industrial processes and whether smaller companies can obtain access to technical advice. Distributed testbeds and cooperation programmes provide routes through which such access may be improved without abolishing the differences between firms. This combination of academic experimentation and industry participation provides a mechanism for reducing uncertainty before firms commit scarce capital. Brno therefore illustrates the value of regional research concentration combined with the need for practical mechanisms of industrial diffusion.

Ostrava offers a complementary case in which manufacturing traditions and contemporary digital engineering meet within a historically industrial region. The Smart Factory laboratory at VSB–Technical University of Ostrava was launched in 2020 as an experimental facility for industrial digitalisation. Its equipment integrates industrial robots, programmable logic controllers, human–machine interfaces and systems for monitoring and recording process information. The laboratory also supports automated material handling and research involving mobile industrial robots. It consequently provides an environment in which students and industry partners can observe how sensing, control and logistics interact within an integrated production process. Such facilities are particularly relevant for regions where existing industrial competences must be connected with newer software-intensive forms of engineering. Educational use is significant because factory digitalisation requires personnel who understand both physical equipment and the logic of industrial information systems. Yet a laboratory’s regional contribution also depends on sustained partnerships, industrial uptake and opportunities for workers already employed in manufacturing. The Ostrava example reinforces the idea that advanced digital production depends on institutions capable of translating technical concepts into repeatable engineering practice.

The semiconductor sector gives the history of Czech industrial digitalisation a different but closely related dimension. Electronic components determine the performance of industrial controls, sensing equipment, power-conversion systems and many devices used in automated factories. Production in Rožnov pod Radhoštěm draws on an established electronics and semiconductor tradition that predates the independent Czech Republic. After 1993, the region’s

industrial base became connected with changing international corporate structures and specialised markets for semiconductor products. The contemporary onsemi manufacturing site combines wafer-related activities with fabrication and design competences relevant to power electronics. According to the company's institutional information, its Rožnov design centre was established in 1993, while the manufacturing operation was acquired through a corporate restructuring in 1999. These dates demonstrate continuity through organisational change rather than the sudden creation of semiconductor expertise in the twenty-first century. The industry's strategic relevance comes from the relationship between specialised manufacturing processes, engineering knowledge and international supply chains. The shared technical language of robotics, digital control and materials processing can strengthen these relationships while preserving regional specialisation. The Czech contribution therefore includes both production capabilities located within the country and the capacity of local specialists to participate in advanced semiconductor development.

Silicon carbide became especially important as demand increased for electronic components capable of managing power efficiently in demanding applications. Compared with conventional silicon devices in some operating regimes, silicon-carbide technology can support designs suited to higher voltages, switching efficiency and thermal performance. These properties have practical relevance for electric vehicles, industrial drives, energy conversion and infrastructure associated with renewable power. The technical challenge extends beyond designing a circuit because wafer quality, process control and reliable packaging influence the performance of manufactured components. Onsemi reported that it had added silicon-carbide wafer and epitaxy production in Rožnov from 2019 and inaugurated an expanded fabrication facility in September 2022. This was an actual industrial development within the period, distinct from larger investment proposals announced later. Its relevance to computer science is partly indirect, since industrial control and energy-efficient computing rely on suitable power-management electronics. It also demonstrates how digital process monitoring and advanced manufacturing methods are required to produce the components used by other technological industries. Czech semiconductor manufacturing thus links the material foundations of electronics with the wider ambitions of industrial digitalisation.

In June 2024, onsemi announced a proposed multi-year investment of up to two billion United States dollars to establish an advanced silicon-carbide production complex in the Czech Republic. The announcement raised the profile of Rožnov within European debates about supply-chain resilience and strategic industrial capabilities. However, an announced investment should not be confused with a completed factory or realised production capacity at the end of 2025. CzechInvest reported in March 2025 that the larger investment phase remained subject to assessment associated with the proposed incentive arrangements. The same account distinguished an earlier approved incentive for a smaller expansion from the much larger project under consideration. This distinction is crucial when evaluating how much additional industrial capability the country actually possessed by the historical endpoint. The proposal nevertheless demonstrated investor interest in an established Czech production location and in its connection with broader European semiconductor demand. Its potential effects on employment, training and supplier development depended on subsequent implementation rather than on the

announcement itself. The site thus illustrates how inherited production expertise can remain relevant when electronic components and their manufacturing methods change. A historically responsible analysis therefore treats the project as evidence of strategic direction and anticipated investment, not as a measurable completed industrial achievement.

National semiconductor policy acquired greater visibility when the Czech government approved the National Semiconductor Strategy in October 2024. The strategy framed chip-related capabilities as an issue of industrial competitiveness, skilled employment and participation in European technological development. It identified the importance of research cooperation, education and investment in a field where production depends on unusually specialised expertise and substantial capital. The Czech Semiconductor Centre was launched in Brno in April 2025 as a mechanism for connecting research institutions with enterprises and emerging chip designers. Its stated activities included advice, support for development and access to relevant European pilot-line opportunities. The centre's opening was an institutional milestone, although its subsequent effects on commercial production and firm creation could not yet be fully assessed in 2025. Semiconductor policy also differs from ordinary software policy because manufacturing facilities require physical infrastructure, specialised materials and long qualification periods. Effective national participation therefore depends upon selecting capabilities where domestic knowledge can complement, rather than duplicate, every stage of an extensive international value chain. The interaction between Rožnov manufacturing and Brno research support exemplifies the geographically distributed nature of contemporary Czech industrial electronics.

The changing scale of industrial digitalisation can be assessed more carefully through national statistical evidence than through exceptional corporate success stories alone. The Czech Statistical Office reported that 16.6% of manufacturing enterprises with at least ten employees used robotics in its 2022 survey. The same publication reported substantial differences between size groups, with robotics used by 7.2% of small manufacturers and 64.3% of large manufacturers. These figures refer to enterprise adoption under specified survey definitions, not to the number of robots installed or the technological sophistication of each individual factory. They nevertheless reveal how investment resources and organisational scale influence opportunities to introduce automated production. Small suppliers may lack dedicated information-technology departments and may find it difficult to justify complex systems that require continuing support. Larger manufacturers can often spread fixed investment costs over greater output and maintain teams responsible for integration, data management and process improvement. This unevenness means that the visible technological frontier cannot be treated as representative of the whole Czech manufacturing economy. At the historical endpoint, the investment represented an important possibility, but its eventual economic effects could not yet be demonstrated. Any evaluation of national progress must consequently combine detailed case studies with comparable indicators of technology adoption and industrial capacity.

The skills required by digitally connected manufacturing extend beyond the traditional division between production workers and software specialists. Engineers must interpret measurements, understand computational assumptions and communicate with colleagues responsible for procurement, maintenance and information systems. Technicians increasingly encounter

interfaces that combine machinery diagnostics with digital documentation, while managers must assess the reliability of automated recommendations. A shortage of appropriate skills can prevent enterprises from extracting value from equipment whose technical specifications appear impressive. Universities and applied research centres therefore play roles in both developing technologies and adapting professional education to changing industrial work. International companies may transfer procedures and training resources into Czech factories, but local learning is needed for those practices to become sustainable. Knowledge transfer also involves the ability of employees to question unsuitable software outputs rather than accept them because they appear computationally sophisticated. The European Commission's 2025 Digital Decade assessment identified continuing weaknesses in business digital transformation despite progress in several foundational capabilities. The central challenge was consequently not to replace industrial expertise with digital competence, but to combine the two in ways that improved decisions and preserved accountability.

By 2025, the Czech Republic possessed a manufacturing ecosystem in which modern digital technologies were applied through several distinct pathways. Some companies integrated imported industrial platforms into production sites belonging to international groups, while others developed specialised machine software with domestic research partners. Universities and testbeds provided controlled environments for experimentation, and semiconductor manufacturers contributed essential components to wider technological supply chains. Evidence from TOS VARNSDORF, Škoda Auto, RICAIP, Ostrava's Smart Factory and onsemi demonstrates the range of industrial roles represented in the country. Their achievements should nevertheless be interpreted according to different standards, including validated research, operating equipment, corporate adoption and still-unrealised investment plans. No single metric can describe the success of a digital transformation that includes productivity, product quality, maintenance reliability, knowledge retention and workforce development. The deeper economic question is whether firms can develop and sustain capabilities that enable adaptation when technologies, customers or production conditions change. Continued progress also requires attention to cybersecurity, energy efficiency, interoperability, training and the uneven resources available to smaller suppliers. Industrial policy also needs to acknowledge that technological progress may legitimately follow different sequences in firms of different sizes. The history of Czech industrial digitalisation thus illustrates a transition from isolated computerised operations towards more closely connected systems of engineering knowledge, industrial information and international production.

Part Four

Leading Institutions, Scientific Schools and Innovation Ecosystems of Czech Information Technology

Digital Transformation of Government and Society: Electronic Public Services, Digital Skills, Inclusion and Economic Modernisation

The digital transformation of Czech government and society between 1993 and 2025 was a prolonged institutional change rather than a succession of isolated technological purchases. It altered relations among public authorities, citizens, businesses and the organisations responsible for maintaining information systems. Computerisation initially aimed to improve administrative recording, but later reforms sought to make services accessible remotely and to exchange trustworthy information across institutions. This distinction matters because placing a form online does not necessarily simplify the administrative procedure behind it. A comprehensive assessment must examine legal validity, organisational coordination, data quality, security, user experience and unequal opportunities to participate. The Czech experience developed through national decisions while increasingly responding to European Union (EU) programmes and common legal requirements. It also depended upon widespread household connectivity, electronic banking and the gradual normalisation of digital communication in everyday life. By 2025, digital government had become a visible component of the national information economy, although access and interoperability remained uneven. The present discussion therefore treats public services, social competences and economic modernisation as interconnected elements of one historical transformation.

The independent Czech Republic inherited administrative information systems whose origins preceded the dissolution of Czechoslovakia in 1993. Public institutions already used computers for population records, taxation, social insurance, statistics and specialised technical tasks. These applications reflected a tradition of centralised record-keeping, but their technical standards and organisational purposes did not form a unified service architecture. Political transformation after 1989 introduced new demands for administrative transparency, private enterprise and accountable management of personal information. The independent state had to maintain essential records while establishing its own ministries, legal responsibilities and financing arrangements. Early reform consequently involved the difficult migration of existing data and work practices rather than immediate replacement by fully integrated systems. Different authorities modernised at different rates because their budgets, information requirements and technical capabilities varied considerably. A fragmented starting point subsequently shaped the costs of connecting information systems and clarifying which public bodies held authoritative records. The endurance of these problems demonstrates that institutional inheritance can influence technological progress long after a constitutional

transition. The years after 1993 thus formed the administrative foundations from which more ambitious public-sector digitisation eventually emerged.

During the 1990s, government computerisation advanced alongside the diffusion of personal computers, commercial software and networked communication. Local authorities and central agencies increasingly acquired digital tools for correspondence, accounting, registration and the management of administrative cases. Their immediate benefits were usually internal improvements in document preparation, retrieval and staff productivity rather than direct public access. The adoption of computers also created new requirements for procurement, technical support, employee training and reliable long-term storage. Citizens generally continued to interact with offices through paper documents, physical attendance and procedures organised around individual agencies. This separation between electronic processing inside an office and traditional contact outside it limited the social visibility of early reform. Moreover, departmental databases could reproduce existing bureaucratic divisions if information exchange was not addressed in system design. The Czech administration therefore confronted the broader problem of turning computerised offices into an interoperable public service environment. Understanding that transition prevents the misleading assumption that a growing number of computers automatically constituted digital government.

Accession to the European Union on 1 May 2004 reinforced the international and legal dimensions of Czech public-sector modernisation. European cooperation increased the relevance of comparable administrative procedures, recognised electronic transactions and cross-border exchange of information. Structural and other European funding arrangements could support infrastructure investments, project management and the development of public services. Nevertheless, financing a technological project and achieving durable administrative reform remained distinct tasks requiring different forms of expertise. Czech institutions had to reconcile national legal traditions with increasingly common expectations concerning access, security and electronic communication. Cooperation also encouraged attention to interoperability, understood as the ability of organisations and systems to exchange and use information meaningfully. Practical interoperability requires shared identifiers, consistent definitions, authorised access and workflows capable of responding to updated records. Without these conditions, information may circulate electronically while still requiring officials to verify or re-enter it manually. European integration consequently provided opportunities and incentives, but domestic governance determined whether those opportunities produced reliable services. This relationship between international frameworks and national implementation remained central throughout the period.

Czech POINT, introduced in 2007, represented a conspicuous attempt to simplify the encounter between citizens and fragmented administrative registers. Its Czech name, Český Podací Ověřovací Informační Národní Terminál, identifies a network of assisted public-administration contact points. Rather than requiring individuals to visit several authorities, participating offices could provide selected authenticated extracts and related administrative services. Municipal offices, post offices and other authorised locations offered a familiar physical interface to information stored in digital systems. This hybrid design acknowledged that public-service modernisation could not assume universal internet access or technical confidence. The service

depended on legal authority, trusted operators, reliable access to records and procedures for authorised document conversion. Its diffusion made administrative digitisation visible outside specialist technological communities and contributed to a more service-oriented understanding of reform. However, it did not eliminate the need for well-designed remote services or the underlying challenge of consistent data across departments. Czech POINT should therefore be understood as an institutional bridge between traditional public counters and increasingly integrated electronic administration.

A second decisive innovation was the introduction of the official electronic data-box system, known in Czech as datové schránky, in July 2009. Act No. 300/2008 Coll. established a legal framework for electronic acts and the authorised conversion of documents. Data boxes provided a recognised channel for delivering official messages between public authorities, legal entities and other eligible users. Unlike ordinary email, this system was designed around identifiable participants, secure transmission and evidence that delivery had occurred. Its adoption changed administrative communication by giving electronic delivery legally significant consequences comparable with established paper procedures. Compulsory use for many organisational categories encouraged the development of compatible internal document-management systems. The legal and technical design also required organisations to consider access rights, retention, workflow responsibilities and the treatment of delivery notifications. For businesses, the system could reduce postal handling and accelerate routine interactions, while simultaneously creating new compliance obligations. Individuals gained additional possibilities for remote communication, although ease of use depended upon authentication and procedural familiarity. The data-box system illustrates how digital transformation can advance when technological infrastructure and enforceable legal rules develop together.

The launch of the basic-registers system on 1 July 2012 addressed a deeper obstacle to effective electronic government. Previously, public institutions frequently maintained separate copies of personal and organisational data that could become inconsistent or outdated. The new arrangement supplied authoritative reference information through interconnected registers with defined purposes and access conditions. A public authority could retrieve relevant verified data rather than repeatedly asking a citizen to document information already held by the state. This principle is often described as allowing data to travel instead of requiring people to travel between offices. Implementing the system nevertheless demanded technically secure interfaces, coordination among record-keeping authorities and careful assignment of responsibility for corrections. Access logging and legally defined permissions were essential because the benefits of interconnection created corresponding privacy risks. The registers did not themselves complete every digital service, but they supplied an important infrastructural condition for subsequent development. Their history shows that information architecture may be more consequential than the public appearance of a website.

Interoperability subsequently became a persistent measure of whether Czech digital government could operate as a coherent system. A citizen-facing portal may appear unified even when different ministries maintain incompatible procedures and disconnected databases behind it. Such fragmentation can require repeated identity checks, duplicate document submission and separate management of the same administrative information. Technical integration alone

cannot solve these problems when legislation allocates overlapping responsibilities or agencies interpret information differently. Effective service design therefore requires common data semantics, transparent accountability and agreements about when an agency may rely on another authority's records. National register infrastructure improved the possibilities for sharing, but complex sector-specific applications continued to evolve independently. The costs of maintaining older systems and replacing established procurement arrangements complicated the creation of shared services. Public-administration research accordingly treats interoperability as an organisational and legal challenge as well as a computational one. The Czech case demonstrates that reform must connect front-office access with the less visible redesign of back-office processes. Where this connection remains incomplete, digitisation risks accelerating existing bureaucracy rather than fundamentally simplifying it.

A broader strategic approach became more explicit with the Digital Czech Republic programme approved by the government in October 2018. Its purpose extended beyond the technical operation of ministries to the digital transformation of the economy and society. The programme connected the country's participation in European digital policy with the modernisation of administration and the readiness of citizens and businesses. This cross-cutting design recognised that investment in online public services would have limited value without connectivity and digital competences. It also acknowledged the importance of coordinating technological change across authorities that had previously developed individual systems. Strategic documents could establish shared objectives, but they still required operational plans, budgets, measurable outcomes and public accountability. Its significance lay partly in changing the policy vocabulary from departmental computerisation towards coordinated transformation. That orientation shaped later discussion of public-sector platforms, digital identity, administrative efficiency and inclusion. The achievement of strategic coherence, however, remained dependent upon sustained implementation rather than policy adoption alone.

The Citizen Portal, or Portál občana, entered trial operation in July 2018 as a personalised gateway to state services. It differed from an informational website because authenticated users could reach individual services and communicate with public authorities. A consolidated interface promised to reduce the need to locate separate agency websites and repeatedly navigate unfamiliar administrative terminology. The quality of this experience depended upon the number of genuinely available transactions rather than the mere presence of links. Reliable identity verification, accessible design and consistent instructions became important determinants of whether the portal could fulfil its purpose. The portal also made the distinction between public information and the protected environment for personal transactions particularly visible. Citizens could increasingly expect that digital administration should resemble other secure online services in clarity and availability. At the same time, differences in departmental readiness limited the pace at which entire procedures could become accessible through one point. The portal's development thus illustrates the gradual shift towards user-oriented government, without implying that all underlying systems were unified. By the middle of the 2020s, it formed an important interface within a broader and still evolving digital public-service architecture.

Trustworthy electronic identification was another prerequisite for expanding the range of public transactions available remotely. A digital service must establish who is acting, what permissions

that person holds and whether the action can be legally attributed to them. European rules on electronic identification and trust services reinforced the need for reliable identities and legally recognised electronic transactions. The introduction of bank identity in 2021 allowed customers of participating banks to use familiar credentials for selected online public services. This model drew on the established relationship between banks, customer identification requirements and secure digital access. Its attraction lay in lowering the practical barrier faced by people who already used internet banking but not government-specific authentication tools. However, a convenient login does not remove every obstacle concerning disability, language, unfamiliar processes or eligibility for particular banking services. Electronic identity must also be distinguished from the legal authorisation required to represent another person or organisation. The Czech experience shows how cooperation with private infrastructure can widen participation while introducing questions of governance and equal access.

Administrative coordination underwent another institutional change when the Digital and Information Agency began operating on 1 April 2023. The agency, known by its Czech abbreviation DIA, was tasked with concentrating important responsibilities for national digital public administration. Its portfolio included major components such as data boxes, the Citizen Portal, Czech POINT and basic registers. This concentration responded to the difficulty of developing interdependent systems through organisational structures divided among multiple authorities. A coordinating institution can encourage consistent service standards, prioritise integration and give users a clearer account of technical responsibilities. It cannot, however, abolish the substantive powers of ministries or remove the legal complexity of individual administrative procedures. Successful coordination also depends upon shared architectural rules, skilled staff, procurement capacity and reliable long-term maintenance. The creation of DIA therefore marked an organisational response to accumulated challenges rather than an instantaneous solution to them. Its early programme included improving existing services and developing new methods of presenting identity in digital form. The reform highlights how the governance of digital systems becomes more important as those systems become essential public infrastructure.

The eDoklady mobile application, launched in January 2024, illustrates the extension of Czech digital services beyond conventional online forms. It allowed holders of valid Czech identity cards to present a digital representation through a supported mobile device in specified circumstances. Acceptance expanded in stages, making the precise date and category of participating institution important when describing its development. The application addressed an everyday interaction in which individuals had previously relied almost exclusively on a physical identity document. Its implementation required secure credential presentation, verification procedures and safeguards against unauthorised disclosure of personal information. Digital identity presentation is related to, but not identical with, authentication for a remote government transaction. The initiative nevertheless reflected rising expectations that official identity services should be convenient, mobile and technically trustworthy. It also introduced new accessibility questions for citizens without compatible devices or sufficient confidence in smartphone applications. The project provides an instructive example of technological convenience that must be evaluated alongside the continuing availability of alternative services.

The legal principle that citizens should be able to obtain public services digitally acquired greater prominence with Act No. 12/2020 Coll., on the Right to Digital Services. Rather than concentrating upon one technology, the legislation addressed the relationship between the individual and the public administration. Its implementation required authorities to reconsider forms, methods of communication and the repeated submission of information already lawfully available. The intended change was procedural as well as technical because a digital transaction must have a recognised legal effect. A useful electronic form should guide the applicant, limit preventable mistakes and acknowledge the successful submission of a request. A coherent service should also provide understandable information about the next procedural step and the responsible authority. The existence of a statutory right cannot be treated as proof that every administrative service was fully digital by 2025. Differences among public bodies, dependencies on older information systems and the complexity of legislation continued to affect implementation. This distinction between legal entitlement and operational maturity is essential when interpreting national progress reports. The reform illustrates the attempt to redefine digital access as a normal feature of public administration rather than a discretionary convenience.

Service design and public procurement became critical factors as digital systems assumed an increasingly central role in public administration. Government platforms have to function reliably over many years, even when software suppliers, technical standards and political priorities change. Procurement based only on immediate delivery can create costly dependence on proprietary interfaces or insufficiently documented systems. Administrative staff need to understand the relationship between automated functions, human discretion and the legal responsibilities of their offices. Designers must also distinguish high-volume routine transactions from complex cases requiring explanation, evidence assessment or individual judgement. Digital services should not transfer the burden of navigating inconsistent rules from officials to citizens merely because a portal is available. Meaningful evaluation therefore considers completion rates, accessibility, accuracy and user confidence in addition to system availability. The OECD's 2023 review of Czech public governance identified digital administration among the fields requiring coordinated institutional improvement. The broader lesson is that technological investment contributes to modernisation only when matched by organisational learning and accountable service management.

Healthcare demonstrates particularly clearly why digitisation involves sensitive information, professional responsibilities and complex institutional relationships. Czech healthcare providers adopted electronic records and specialised clinical software at different speeds, reflecting differences in resources and organisational scale. The national electronic-prescription system, eRecept, became mandatory from 1 January 2018, subject to statutory exceptions. Electronic prescribing linked medical practitioners and pharmacies through a central infrastructure for issuing and dispensing medicines. The system could reduce some risks associated with illegible paper prescriptions and improve the traceability of prescription transactions. Its operation nevertheless depended upon secure access, reliable connectivity and processes for handling exceptional situations. Electronic prescribing should not be confused with a fully integrated personal health record containing all clinical information across providers. Such integration additionally requires common standards, governance of access and the willingness of

institutions to exchange information appropriately. The Czech example thus shows the difference between digital success within a bounded clinical workflow and comprehensive transformation of a national health system. It also illustrates why patients' privacy and the continuity of treatment must remain integral to technological design.

The coronavirus pandemic beginning in 2020 exposed both the potential and limitations of digitally supported public services. Authorities had to communicate rapidly, process changing information and maintain essential interactions while physical contact was restricted. Schools, healthcare providers, municipalities and public agencies consequently relied more heavily upon online channels and remote communication. The crisis demonstrated that an operational website was insufficient when large numbers of users simultaneously required dependable transactions and clear instructions. It also revealed how inconsistent data or difficult interfaces could undermine confidence during periods of exceptional uncertainty. Social insurance administration also expanded electronic procedures, including the nationwide implementation of electronic sick-leave certificates in 2020. The emergency accelerated practical adoption but did not eliminate differences in the digital readiness of public bodies and households. A balanced historical interpretation must therefore distinguish temporary crisis measures from institutional improvements that remained useful afterwards. The pandemic strengthened the argument for resilient services designed around real users rather than around isolated administrative applications.

The expansion of electronic healthcare sharpened questions about who may access personal medical information and for what purpose. Health data can support better treatment, clinical research and public-health planning, but their sensitivity demands especially careful governance. Electronic systems must define the responsibilities of patients, practitioners, hospitals, insurers and public authorities without confusing their different roles. Cybersecurity measures are important because unavailable or altered clinical information may affect health outcomes rather than merely administrative convenience. Equally significant are consent where legally required, access logging, secure identity verification and procedures for correcting inaccurate data. European personal-data rules provide a common legal framework, yet the design of operational safeguards remains an institutional responsibility. A patient-facing digital service should communicate what information is available and how it may be used without assuming specialist knowledge. Interoperability can improve continuity of care when records follow an authorised clinical purpose, but unrestricted information exchange would be inappropriate. The pace of implementation must therefore be assessed by trustworthy access and clinical usefulness, not only by the quantity of digitised documents. These challenges demonstrate why the development of information technology in healthcare is inseparable from ethics and public confidence.

Education was another major setting in which computer technology gradually changed the social experience of modern Czechia. During the 1990s, access to school computers and introductory informatics varied with institutional resources and local development. The educational significance of technology nevertheless depended upon teachers' competences and the suitability of software for particular learning objectives. Providing equipment could widen opportunities, but it could not replace curriculum development or professional preparation.

Universities also expanded programmes in computing, information systems and related engineering fields in response to changing employment demand. The relationship between education and the information economy consequently operated in two directions, since industry needed skilled graduates while new technologies influenced teaching. Digital competence increasingly involved evaluating information, protecting privacy and using computational tools responsibly rather than simply operating devices. An education system able to cultivate these capabilities could support both economic competitiveness and informed civic participation. The historical challenge was to make such opportunities available beyond the best-resourced institutions and metropolitan regions.

The Strategy for the Education Policy of the Czech Republic up to 2030+, approved in October 2020, placed competence development and educational equality among its central concerns. Its priorities included the modernisation of curricula, digital education and the reduction of disparities in access to quality learning. These objectives became particularly salient as schools confronted the need for remote teaching during the pandemic. Distance education could preserve continuity for some students while magnifying disadvantages associated with inadequate devices or unstable home connections. Teachers needed preparation not only for using communication platforms but also for assessing learning and sustaining meaningful interaction remotely. Digital teaching materials had to accommodate age, subject matter and diverse educational needs rather than reproduce classroom procedures mechanically. The experience encouraged greater attention to educational resilience and the ability to combine face-to-face and online methods appropriately. It also underlined the importance of technical support, safe platforms and participation by parents who might themselves have limited digital experience. National educational reform therefore connected computer technology with pedagogy, social policy and the organisation of public services. Its results cannot be measured adequately by counting devices without examining the quality and distribution of learning opportunities.

The preparation of information and communication technology (ICT) specialists linked national education directly with the growth of the digital economy. Czech universities and technical institutions trained programmers, systems engineers, security specialists, data professionals and researchers across different regions. Private companies, public agencies and scientific organisations competed for many of the same graduates, particularly in specialised technical fields. Formal degrees offered systematic foundations, while short courses and workplace learning helped employees adjust to changing tools and procedures. However, shortages of specialists could make it difficult for public bodies to retain expertise or supervise technically demanding contracts. An administration that relies entirely on external suppliers may struggle to evaluate performance or preserve institutional knowledge. The European Commission’s 2025 assessment recorded ICT specialists at approximately 4.5% of Czech employment, below the EU figure of 5.0%. This indicator does not capture every technical occupation, but it provides useful context for the competition over advanced digital capabilities. Sustainable public-sector modernisation consequently requires career pathways and continuing education alongside technological investment.

Digital inclusion remained a substantive challenge even as internet access became a routine feature of Czech social life. The Czech Statistical Office reported that approximately 88 per cent of people aged sixteen and above used the internet in 2024. Among people younger than fifty-five, usage was almost universal, whereas participation was substantially lower among older residents. These differences show why population averages can conceal significant disadvantages in access to public services. Education, disability, income and confidence in navigating unfamiliar procedures may matter even when a broadband connection is available. A person might use online banking or messaging successfully while remaining uncertain about authenticated government documents. Administrative services often involve legal language and consequential decisions, which can increase anxiety about making an irreversible mistake. Accessible digital design therefore requires clear explanations, predictable navigation, meaningful error messages and reliable opportunities for assistance. Public authorities also need to preserve routes for people who cannot reasonably undertake particular actions online. The objective should be equal practical access to rights and services rather than the elimination of every non-digital channel.

The digital divide within Czechia cannot be described accurately as a simple opposition between connected cities and disconnected countryside. Regional infrastructure, income, educational attainment and age profiles overlap in ways that can produce different patterns of disadvantage. A smaller town may have reliable connectivity but limited local opportunities for advanced digital training or specialist employment. The rapid normalisation of smartphones changes the devices through which citizens participate, but it does not remove differences in capability. Some administrative processes remain difficult to complete on a small screen, particularly when several documents must be reviewed or uploaded. Public libraries, municipal centres and assisted service points can consequently contribute to inclusion beyond their traditional informational functions. Reliable measurement should distinguish availability of networks, actual use, task-specific skills and the successful completion of administrative procedures. The Czech experience demonstrates the importance of treating digital equality as a multidimensional social question. Policies based on aggregate connectivity alone may overlook the obstacles experienced by the people most dependent upon public services.

Financial services played a major role in normalising secure digital interaction for Czech households and enterprises. Banks introduced internet and mobile banking, giving many customers practical experience with remote authentication and sensitive transactions. By the early 2020s, these habits helped make electronic identity through participating banks a credible route to government services. The transfer of familiar authentication methods to public administration nevertheless required explicit legal and technical arrangements. Electronic payment systems also supported e-commerce, public fees and the wider information economy by reducing reliance on physical cash-handling. At the same time, phishing, fraudulent messages and social engineering created risks that could undermine trust in digital transactions. Users needed skills to verify service addresses, understand authentication prompts and recognise requests for unnecessary personal information. Public authorities could benefit from private-sector experience in transaction design while retaining their distinctive responsibilities towards citizens. Commercial convenience and universal public-service access are not identical,

especially where an individual lacks a bank account or compatible device. The relationship between finance and government therefore illustrates both the promise and the limitations of sharing digital infrastructures across sectors.

Electronic commerce and everyday communication further shaped public expectations of digital services throughout the period. Consumers became accustomed to searching for information, comparing alternatives, arranging deliveries and receiving electronic confirmation of transactions. These experiences generated expectations of speed and transparency that were also directed towards public administration. Nevertheless, a government decision is not interchangeable with a commercial purchase because it involves legal rights, due process and public accountability. For this reason, rapid completion cannot be the sole criterion for evaluating an electronic administrative procedure. Users must understand how a decision was reached, what information was considered and how an error may be challenged. Digital technologies can improve the traceability of decisions when records are designed carefully and preserved in accessible formats. They can also obscure responsibility if automated interfaces provide no meaningful explanation of the underlying administrative process. The modernisation of public services therefore requires both the practical convenience of digital transactions and the safeguards of lawful government.

Regional and municipal administrations became important laboratories for practical digital transformation in Czechia. Local authorities handled matters closely connected with daily life, including selected registrations, local fees, permits and public information. Their systems had to connect with national registers while responding to the financial and administrative circumstances of individual communities. Large municipalities could develop specialised teams and integrated portals, whereas smaller offices often relied upon shared platforms or external support. This uneven capacity made nationwide services such as Czech POINT especially important outside major urban centres. Digitised geographical information and municipal data also created opportunities for more transparent planning and public communication. However, the publication of datasets needed clear licensing, documentation and safeguards against disclosure of protected information. Effective local innovation depended upon cooperation between technical specialists, administrators and residents whose needs could differ substantially. A common national architecture could reduce unnecessary duplication while leaving appropriate room for local administrative responsibilities. The regional dimension demonstrates that the success of digital government depends upon implementation across the whole state, not only at central ministries.

Accessibility and assisted participation should be considered permanent components of a well-designed digital public-service system. An online form that is difficult to navigate with assistive technology can exclude citizens despite being technically available at all hours. Complex authentication processes may be especially challenging for people with certain disabilities or limited technological experience. Clear language, keyboard navigation, readable contrast and error messages that explain corrective action are therefore important design considerations. Face-to-face assistance can remain valuable where a transaction concerns a sensitive benefit, an unfamiliar legal duty or a difficult personal circumstance. Czech POINT illustrates how digitally connected staff can help citizens obtain official services through a physical contact point. Such

approaches allow public administration to combine efficiency with procedural fairness instead of treating non-digital access as failure. Inclusion can also improve system quality because services understandable to vulnerable users are often clearer for everyone. A mature digital state should offer meaningful choice while maintaining equivalent legal protection across available service channels.

Cybersecurity and data protection became essential conditions for public confidence as more governmental transactions moved into electronic systems. A single compromised identity or unavailable register can affect multiple services when information infrastructures are interconnected. Authorities therefore need to manage authentication, authorisation, audit trails, backup arrangements and incident response as continuous responsibilities. The General Data Protection Regulation (GDPR) has applied throughout the European Union since 25 May 2018, shaping obligations regarding personal data. However, formal compliance does not by itself demonstrate that a service is understandable, trustworthy or resistant to operational failure. Security controls must be proportionate and usable, since confusing procedures may encourage unsafe workarounds by citizens or staff. The expansion of mobile identity, data boxes and integrated registers increased the importance of maintaining consistent protections across institutions. Transparency about data use and straightforward mechanisms for correcting errors can strengthen legitimacy alongside technical measures. Public information campaigns should therefore address practical digital risks rather than relying solely on declarations of system security. The Czech experience confirms that cyber-resilience and public trust are inseparable from the routine quality of service delivery.

International evaluation provides a useful perspective on Czech digital government, provided that the limitations of composite indicators are recognised. The European Commission's 2025 Digital Decade assessment described substantial strengths in basic digital skills and advanced mobile coverage. It also identified continuing weaknesses in very-high-capacity fixed networks, business digitalisation and aspects of digital public services. In the same assessment, Czechia's digital public services indicators improved, but comparative performance varied between citizens, enterprises and health records. The Czech Statistical Office's Information Society in Figures 2025 provides complementary evidence on households, public administration, health and education. Surveys of users are particularly important because the existence of a service does not establish whether citizens know how to use it. Administrative statistics, meanwhile, can record transactions but may say little about frustration, accessibility or unresolved requests. A rigorous evaluation therefore combines infrastructure measures, service availability, participation and the quality of administrative outcomes. The resulting picture is one of substantial change by 2025, alongside persistent challenges that cannot be described as merely technical.

By the end of 2025, Czech public administration operated within a considerably more developed digital environment than it had inherited in 1993. Electronic data boxes, basic registers, a personalised Citizen Portal, bank-based authentication and mobile identity documents represented distinct but connected stages of that development. The wider society had also become more digitally experienced through education, commercial services, everyday internet use and changing professional requirements. Nevertheless, the coexistence of advanced platforms with fragmented processes meant that institutional transformation remained

incomplete. Differences in age, education and accessibility continued to affect who could make effective use of digitally delivered public services. Public bodies also faced continuing responsibilities for staff development, procurement, data governance and resilient infrastructure. The historical significance of the Czech case lies less in a single technological invention than in the effort to reshape ordinary relations between the state and society. This effort depended on interaction among legal reform, administrative organisation, information engineering and the capacities of individual users. The most reliable measure of future progress is whether citizens and enterprises can complete legitimate tasks accurately, securely and without unnecessary repetition. Digital transformation should accordingly be understood as a continuing public-governance commitment with substantial economic and social consequences.

Prague Computer Science School: Charles University, Czech Technical University and Advanced Information Technology Research

The Prague school of computer science between 1993 and 2025 developed through the interaction of long-established university traditions and changing approaches to computation. Its institutional centre was not a single laboratory but a constellation of departments, research groups, doctoral programmes and collaborative networks distributed across the capital. Charles University preserved a particularly strong connection between mathematics, logic, linguistics and theoretical computer science, while the Czech Technical University in Prague cultivated engineering-oriented informatics and cybernetics. The complementary orientation of these institutions gave Prague a capacity to investigate abstract computational questions and test their relevance in functioning technological systems. The separation of Czechoslovakia in 1993 changed administrative responsibility for research without eliminating intellectual relationships established during the preceding decades. At the same time, the new environment exposed research teams to stronger international competition, new sources of funding and rapidly developing computing methods. The scientific significance of Prague therefore lies neither in the numerical concentration of institutions nor in a simple succession of individual inventions. It lies in the continuity of specialised research traditions that acquired new forms through international collaboration and interdisciplinary experimentation. This chapter examines that institutional development through identifiable scientific contributions, the formation of research communities and their interactions with wider European technology.

Historical interpretation must begin before independence because important Czech computing traditions were already firmly established within the Czechoslovak university system. The Faculty of Mathematics and Physics of Charles University, formed in 1952, inherited traditions of mathematical reasoning that proved essential to subsequent research in informatics. At the Czech Technical University, the development of computing education was closely associated with the Faculty of Electrical Engineering and the wider study of technical cybernetics. The

university's official departmental history dates the establishment of its specialist computer-science department to September 1964, following the organisation of a computer laboratory in the preceding year. Research and teaching then involved the adaptation of computer architectures, compilers and programming systems to technologies available in Czechoslovakia. Such work required theoretical knowledge, engineering judgement and the practical skills needed to operate heterogeneous equipment under constrained conditions. Even when access to international devices was restricted, specialised expertise accumulated through postgraduate education and the maintenance of computational laboratories. The political opening of 1989 permitted freer academic exchanges and substantially enlarged access to foreign publications, equipment and professional organisations. Consequently, the institutional watershed of 1993 should be distinguished from the earlier opening of scientific communication rather than treated as its origin. The mature Prague research environment was built by adapting these inherited capabilities instead of reconstructing computing science from the beginning.

Charles University's principal setting for computing research was its Faculty of Mathematics and Physics, where mathematical and software-oriented communities developed in productive proximity. The faculty's later School of Computer Science brought together organisational units with different objects of investigation and professional cultures. The Department of Applied Mathematics retained strengths in graph theory, discrete structures, geometry, optimisation and the theory of algorithms. The Department of Theoretical Computer Science and Mathematical Logic concentrated on formal reasoning, constraint satisfaction, automated planning, knowledge representation and related areas of artificial intelligence. The Department of Software Engineering investigated databases, information retrieval, distributed processing and complex software systems with both theoretical and applied dimensions. Other university groups advanced dependable software, natural language processing and the computational analysis of richly structured linguistic information. Their interaction was intellectually significant because research questions frequently crossed the boundaries suggested by departmental names. A problem in language understanding might require statistical inference and efficient algorithms, while software verification might rely upon logic, automata theory and mathematical modelling. The faculty therefore illustrates how disciplinary specialisation and interdisciplinary cooperation can coexist within a comparatively compact academic environment.

The theoretical-computer-science tradition at Charles University was particularly visible through the work of Jaroslav Nešetřil and the Prague community of discrete mathematicians. After 1993, the group combined established research in graph theory with broader investigations of relational structures, combinatorial complexity and constraint satisfaction. Its international intellectual influence was not confined to isolated theorems but extended to the formulation of frameworks for classifying families of mathematical objects. The creation of the Centre for Discrete Mathematics, Theoretical Computer Science and Applications, known as DIMATIA, in 1996 helped institutionalise collaboration across disciplinary and national boundaries. The research school encouraged sustained exchanges among mathematicians, computer scientists, visiting scholars and doctoral students rather than organising knowledge around a single application sector. An important later organisational development was the Computer Science Institute of Charles University, which supported advanced theoretical research and doctoral training. These

initiatives created conditions in which researchers could pursue long-term questions whose technological implications were not immediately predictable. The relationship between Prague's graph-theoretic traditions and computer science is best understood through algorithms, logical definability and the structural properties that govern computational difficulty. It demonstrates that theoretical research can shape new computational methods without becoming subordinate to short-term commercial objectives (Nešetřil & Ossona de Mendez, 2012). The school thus occupies an important position within both the national mathematical tradition and the international study of discrete computation.

Research on sparse graphs provides a particularly clear illustration of how the Prague theoretical school contributed to international computer science. Jaroslav Nešetřil and Patrice Ossona de Mendez developed a systematic treatment of sparsity that connected graph structure with combinatorics, model theory and algorithmic behaviour. Their 2012 monograph Sparsity: Graphs, Structures, and Algorithms presented a broad framework for distinguishing classes of sparse relational structures. Such distinctions matter because algorithms that are intractable on unrestricted inputs may admit effective methods on suitably structured graph classes. The importance of the work therefore extends from structural mathematics towards parameterised reasoning, descriptive complexity and constraint satisfaction. It would nevertheless be misleading to regard the entire approach as an exclusively national invention, given the authors' international collaboration and the earlier foundations of graph theory. What can be identified is the substantive contribution of a Prague-centred research tradition to a research programme of worldwide interest. The publication also shows why internationally recognised scientific contributions must be assessed through precise statements, methods and subsequent applications rather than institutional prestige alone. This criterion guides the treatment of the other Prague research groups considered here.

Another part of the theoretical ecosystem concerned algorithm design, online decision-making, optimisation and computational complexity. Jiří Sgall and collaborators investigated online scheduling, approximation algorithms and related problems in which a system must make decisions without complete information about future requests. These problems differ from ordinary offline optimisation because the decision-maker cannot assume that the entire sequence of tasks is known in advance. Their mathematical formulation allows researchers to establish rigorous performance guarantees and to identify limits that no algorithm can avoid under specified assumptions. This type of investigation has conceptual relevance to computing platforms, resource allocation and scheduling, although a mathematical result does not automatically become a deployed industrial solution. Researchers associated with Charles University also contributed to complexity theory, proof systems and the foundations of computational reasoning. The institution's strength lay in bringing questions from discrete mathematics into contact with computational models that could be analysed formally. Such theoretical research benefited from seminars, international visitors and doctoral work that sustained expertise across academic generations. The resulting Prague school was therefore defined by a continuing set of research problems and methods rather than by a fixed list of prominent individuals. Its influence is most accurately described as a contribution to shared international theory, not as exclusive ownership of algorithms used worldwide.

Mathematical logic and automated reasoning formed a connected but distinct component of Prague's scientific identity after 1993. Logical research provided methods for investigating what may be inferred from formal premises, how knowledge can be represented and which computational procedures preserve correctness. Within Charles University, work on automated planning and constraint programming created important bridges between symbolic reasoning and practical decision-making. Roman Barták investigated techniques that combine scheduling requirements, state transitions and constraints, including methods for modelling changes in dynamic problem environments. His work on regular or automaton constraints illustrated the possibility of embedding finite-state descriptions within general constraint-solving systems. These methods matter for robotics and production planning because feasible behaviour depends upon both the availability of resources and permissible sequences of actions. The Prague contribution in this area should not be confused with the invention of constraint programming as an international discipline. Its importance lies in specialised formulations, research tools, publications and exchanges that made Prague an active participant in the development of that discipline. The intellectual connection between logic and planning became especially valuable as autonomous systems required explicit representations of goals, actions and uncertainty.

Research in software engineering at Charles University represented a different approach to creating reliable computational systems. Instead of treating programs exclusively as sequences of statements, researchers examined their architectures, interactions, interfaces and changing operational environments. Work associated with František Plášil and the Department of Distributed and Dependable Systems (D3S), helped develop methods for constructing component-based applications. The SOFA component-model research programme investigated hierarchical composition, behavioural specifications and ways of reasoning about interactions between independently developed units. A 2006 publication by Tomáš Bureš, Petr Hnětynka and František Plášil set out features of the SOFA 2.0 component framework. The approach addressed a persistent engineering difficulty: a component may operate correctly in isolation while behaving incorrectly when integrated into a larger system. Formal descriptions of permitted communication and verification procedures can expose incompatibilities before deployment, although scalability remains a demanding challenge. This research was especially relevant to distributed applications whose components evolve independently and communicate across unreliable networks. The Prague school thereby connected foundational models of software correctness with engineering problems arising in increasingly interconnected systems. Its significance belongs to the advancement of design methods rather than simply the production of one software package.

The further development of dependable-systems research expanded the scope from conventional component architectures to adaptive and cyber-physical software. Researchers considered how distributed applications can maintain acceptable behaviour when their participants, communication links or environmental conditions change. This problem becomes acute in systems that combine sensors, computational services, mobile devices and physical actuators. Verification has to account for concurrency, delayed communication, partial failures and requirements that may change while a system is operating. Research on model-driven design and adaptive coordination sought to make such behaviour describable before expensive or

safety-sensitive deployment. Theoretical results became connected with experimental platforms and collaborations involving other universities and industrial partners. The scientific value of these investigations lies partly in identifying where conventional testing cannot provide adequate confidence in complex behaviour. At the same time, a formal model is useful only when its assumptions reflect the relevant properties of the real system. This combination of mathematical rigour and engineering realism became a distinctive feature of Prague research on distributed and dependable software.

Computational linguistics provides an especially revealing example of continuity between traditional Czech scholarship and advanced information technologies. The linguistic research environment of Charles University developed from earlier Prague traditions in structural linguistics, formal semantics and the analytical description of grammatical relations. After 1993, the Institute of Formal and Applied Linguistics strengthened the connections between linguistic theory, annotated corpora, algorithms and statistical modelling. Researchers faced a language with rich morphology and flexible word order, making Czech a demanding test case for automatic grammatical analysis. The Prague Dependency Treebank became a prominent resource through systematic annotation at morphological, syntactic and deeper representation levels. Jan Hajič's 1998 account of the project documented the research rationale for creating a syntactically annotated Czech corpus. Eva Hajičová, Jarmila Panevová and their colleagues contributed intellectual traditions that informed the annotation principles and their linguistic interpretation. The project connected human linguistic expertise with machine-readable data structures, enabling algorithms to learn from observations that were carefully checked by specialists. Its lasting value includes reproducible datasets, annotation standards and research questions that extend well beyond the Czech language. The Prague case illustrates how national linguistic particularities can stimulate methodological innovations of international significance.

The development of language technologies continued beyond corpus creation towards reusable research software and multilingual infrastructure. Morphological analysers, part-of-speech taggers, dependency parsers and named-entity recognition tools emerged from the interaction of annotated data and statistical or neural methods. Research by Milan Straka, Jan Hajič and Jana Straková produced UDPipe, a trainable system for tokenisation, morphological processing and dependency parsing. Their 2016 publication demonstrated how a common processing pipeline could support many languages through compatible annotated resources. This achievement mattered because a research group otherwise needs several separately maintained components before performing more sophisticated language tasks. By using a shared data representation, the system reduced barriers to replication and comparative evaluation across languages. The underlying scientific contribution concerned practical modelling and linguistic data processing rather than the claim to have invented neural language technology. Prague researchers also participated in international efforts to harmonise dependency annotation and increase the availability of linguistic resources. These activities demonstrated how expertise developed for Czech could contribute to broader multilingual computational research. The combination of publications, datasets, software and institutional stewardship strengthened Prague's position in international language technology. The availability of reusable, documented tools also supported teaching and independent evaluation outside the institute’s own research programmes.

At the Czech Technical University in Prague, the historical trajectory of informatics developed through electrical engineering, control systems and technical cybernetics. Its Faculty of Electrical Engineering combined theoretical foundations with practical research concerning processors, sensors, networks and automated industrial systems. The departmental computer-science tradition established in the 1960s entered the post-socialist period with experience in operating computing equipment and teaching programming. After 1989, international cooperation and curricular reform increasingly connected that experience with contemporary algorithms, software development and computer engineering. The growth of specialist teaching was not simply a response to commercial demand because the university also developed original research programmes. Computer-science education became more closely linked with laboratories investigating robotics, machine learning, distributed systems and the analysis of complex data. The institutional environment nevertheless differed from Charles University's primarily mathematics-led traditions through its emphasis on engineered devices and measurable performance. These differences were complementary rather than mutually exclusive, since both universities needed knowledge of logic, mathematical optimisation and computing architectures. By 2025, Prague's scientific strength rested substantially on the coexistence and communication of these academic cultures.

The establishment of the Center for Machine Perception at the Czech Technical University in 1996 marked a notable stage in the organisation of Prague computer-vision research. The centre developed as a cooperative network of groups rather than a conventional department with a rigid administrative boundary. Its participants investigated visual recognition, pattern analysis, geometric reconstruction, autonomous robotics and biomedical image processing. Václav Hlaváč played an important role in the centre's formation, while later research involved specialists such as Jiří Matas, Tomáš Pajdla and Jan Kybic. Computer vision requires more than recognising an object in a photograph because algorithms must respond to viewpoint, scale, illumination, occlusion and sensor imperfections. Mathematical geometry, statistical estimation and efficient implementation therefore became closely connected within the Prague research environment. The centre's interdisciplinary organisation helped investigators address problems requiring several kinds of technical expertise and different forms of experimental evidence. It also provided an academic context in which doctoral students could move between mathematical methods and practical image-processing tasks. The significance of the centre is illustrated by identifiable research contributions rather than its institutional title alone. Its emergence demonstrates the importance of flexible research networks within a technically specialised university. That institutional breadth would later support partnerships with the university’s more specialised computer-science faculties and institutes.

Research on robust image correspondence became an internationally visible contribution associated with the Prague computer-vision school. Jiří Matas, Ondřej Chum, Martin Urban and Tomáš Pajdla investigated how stable visual structures could be matched across photographs taken from different perspectives. Their work on maximally stable extremal regions developed a method for identifying image regions resistant to certain geometric and photometric transformations. The 2002 conference contribution and its later journal version provided a concrete methodological advance in wide-baseline image matching. Such correspondences can

help infer spatial relationships between cameras and are relevant to image retrieval and three-dimensional scene reconstruction. The scientific achievement was not the complete solution of visual understanding but a specialised approach to a persistent and well-defined recognition problem. Subsequent work from Prague groups investigated robust estimation and recognition under challenging visual conditions, often within international collaborative teams. The methodological lesson is that dependable perception frequently requires careful treatment of uncertainty and outliers rather than larger amounts of raw image data alone. This emphasis on algorithmic robustness helped connect theoretical image analysis with robotics, multimedia systems and industrial inspection. The example also illustrates how a relatively small research team can contribute techniques adopted far beyond its original institutional environment.

The progress of Prague computer vision also depended on collaboration between geometrical analysis, machine learning and the growing availability of digital image collections. Researchers investigated feature extraction, recognition and visual localisation under conditions that could not be controlled as tightly as laboratory demonstrations. The question of reproducibility became more important as large datasets and common evaluation protocols were introduced into international computer-vision competitions. Prague teams increasingly published methods alongside comparisons intended to demonstrate generalisation beyond examples selected by the authors themselves. This practice offered a way to separate genuinely robust algorithms from procedures that worked only on a limited collection of images. Biomedical imaging research at the Faculty of Electrical Engineering extended these concerns to tissue analysis, registration and the interpretation of medical scans. Work associated with Jan Kybic illustrates how computational methods can assist medical investigation while remaining dependent upon careful validation and professional interpretation. Such interdisciplinary research cannot be represented accurately as the replacement of clinicians by computer vision, since the intended relationship is more often analytical support. The scientific identity of the Prague school was strengthened by this movement between mathematical method, measurable experiments and responsible application.

Artificial intelligence at the Czech Technical University developed through a research tradition that connected symbolic reasoning, intelligent agents and engineering decision-making. The Artificial Intelligence Center was established in 2001 under the leadership of Michal Pěchouček, creating a recognisable organisational setting for work across multiple artificial-intelligence directions. Researchers investigated autonomous agents, coordination strategies, planning, game theory and the management of complex interactions among independent participants. These approaches are useful when a computational environment contains many entities whose goals, knowledge and available resources may differ. Multi-agent research introduced questions that cannot be reduced to improving the classification accuracy of an isolated neural network. It considered the rules under which several intelligent actors can cooperate, negotiate, adapt or compete while operating within practical constraints. The centre’s applied orientation encouraged research relationships with industrial partners and organisations concerned with transportation, security and other complex domains. An important contribution was the cultivation of doctoral and postdoctoral expertise capable of translating formal reasoning into experimental systems. Its history exemplifies the evolution from small specialist groups to

internationally connected research environments within Czech technical education. Prague's artificial-intelligence identity consequently emerged from a diversity of methods rather than from the exclusive dominance of a single technological paradigm.

The work of Michal Pěchouček and his collaborators helped connect Prague's multi-agent research with both international scholarship and practical technology development. Agent-based approaches studied how distributed participants could coordinate routes, tasks or responses when centralised control was undesirable or impossible. Research programmes on autonomous air-traffic management and related planning problems provided demanding scenarios for evaluating these concepts. The AgentFly initiative illustrates the connection between academic work on agents and engineering experiments involving autonomous aerial operations. The questions raised by such systems include communication delays, conflicts between individual plans and the safe management of shared space. Their investigation requires mathematical modelling, software engineering, simulation and controlled testing, not merely the adoption of popular artificial-intelligence terminology. Pěchouček also participated in commercial ventures, including Cognitive Security, creating links between academic research and entrepreneurial activity. However, institutional contribution, individual entrepreneurship and subsequent corporate ownership represent different forms of achievement and should be described separately. The enduring significance of this research lies in methods, specialist training and collaborative projects that extended beyond one university laboratory.

The development of robotics provided another expression of the relationship between informatics and engineering at the Czech Technical University. Research groups studied autonomous mobility, perception, motion planning, coordination and interactions between robotic devices and their surroundings. The presence of computer-vision specialists made it possible to connect measurements from cameras with decisions about movement and navigation. Robotic systems nevertheless depend equally upon mechanical constraints, control stability, energy availability and the quality of sensor information. Prague researchers consequently addressed practical performance alongside theoretical questions of planning and estimation. Work associated with Martin Saska investigated the coordinated operation of small unmanned aerial vehicles in settings requiring reliable relative localisation and control. Experiments with on-board perception and collaborative flight contributed identifiable research results within the broader international study of aerial robotics. Such projects also create valuable educational environments because students encounter software, hardware and safety requirements simultaneously. The Prague school thus illustrates the growing importance of integrated systems research in which computation must interact with physical processes. The relevant scientific outcome is not the visibility of a flying demonstration alone, but the reproducible methods that make a particular robotic capability possible.

The establishment of the Czech Institute of Informatics, Robotics and Cybernetics, (CIIRC), represented a major institutional milestone in Prague's later development. The Czech Technical University established the institute on 1 July 2013 after decisions concerning its scientific mission and organisational framework. Its purpose was to bring together specialists in informatics, control, robotics and related areas while strengthening links with external research and industry. The new building in Prague's Dejvice district entered operation in 2017, providing a more

concentrated environment for researchers and advanced technical facilities. The development should not be interpreted as the sudden creation of informatics or robotics at the university, since relevant expertise had existed for decades. Rather, the institute represented a reorganisation intended to increase visibility, support collaboration and provide an environment attractive to international specialists. Research orientations included machine learning, control, intelligent decision systems, computer vision and software-intensive technological applications. The programme also created stronger opportunities for connecting doctoral education with interdisciplinary and industry-facing projects. Its importance therefore lies in the consolidation and expansion of research capacity, not simply in the construction of a new academic building.

An important characteristic of CIIRC was its attempt to connect university research with experimental environments relevant to industrial transformation. The institute supported work related to intelligent manufacturing, robotics, production planning, data-based monitoring and human-machine cooperation. Research and technology transfer increasingly interacted through shared test facilities in which experimental configurations could be developed and observed. This model differs from a conventional contract in which a university delivers a predetermined software tool for immediate deployment. A testbed can expose researchers and firms to difficult integration questions before an investment is replicated in an operating factory. It can also reveal the limits of artificial intelligence when industrial data are incomplete, organisational procedures are inflexible or safety requirements are poorly specified. International projects such as the Research and Innovation Centre on Advanced Industrial Production, (RICAIP), linked Prague facilities with partner institutions and other industrial research environments. Such collaboration made industrial experimentation a research activity requiring systematic measurement, methodological transparency and comparison with alternative solutions. The institutional significance of CIIRC was therefore closely connected to its ability to convene specialists who otherwise might have remained within separate faculties or firms. The long-term challenge was to sustain this cooperation through adequate operating finance, scientific autonomy and training of successive research generations.

The Faculty of Information Technology at the Czech Technical University introduced another distinctive institutional configuration in Prague's computing landscape. Established on 1 July 2009, the faculty provided a dedicated academic setting for programmes and investigations primarily concerned with informatics and related computational disciplines. Its emergence reflected the growth of computer science beyond the organisational boundaries of traditional electrical-engineering education. The new faculty developed advanced study in areas such as algorithms, computer systems, software and information technologies, while maintaining connections with other technical fields. A separate faculty can clarify the academic identity of informatics, but it does not automatically overcome fragmentation between departments or research programmes. Its value depends upon research quality, coherent doctoral pathways and the ability to collaborate across the wider university. Within Prague, the new institution expanded opportunities for specialist training at a time of increasing demand for sophisticated digital competencies. It also contributed to the diversification of the capital's computer-science community beyond the two older faculties most commonly associated with the discipline. The relationship among Charles University, the Faculty of Electrical Engineering and the Faculty of

Information Technology became increasingly important for advanced computing education. This institutional diversification enlarged the range of academic pathways while making cooperation across administrative boundaries an enduring practical necessity. The institute's creation thus responded simultaneously to scientific specialisation, the expansion of digital education and the demand for advanced information-technology research.

The relationship between Prague computer-science research and doctoral education was central to the durability of its scientific schools. Formal departments transmit established knowledge through courses, but research communities reproduce themselves through seminars, supervision and participation in unresolved problems. Doctoral students learn not only techniques but also standards for testing evidence, reporting limitations and responding to critical examination. At Charles University, theoretical and mathematical programmes offered environments in which research questions could remain intellectually demanding without immediate commercial application. At the Czech Technical University, laboratories and engineering projects provided opportunities to test algorithms against practical constraints and measurable performance requirements. Both approaches benefited from international visiting researchers, joint projects and publication in competitive scientific venues. The circulation of graduates between academia, industrial laboratories and foreign institutions created opportunities for exchanging methods and acquiring expertise. It also generated a retention challenge, since research careers in larger technology economies could provide attractive alternatives to domestic positions. An effective Prague research ecosystem therefore required not only distinguished senior scholars but also credible career pathways for younger investigators.

Scientific publication and international assessment reshaped the visibility of Prague computing research after 1993. Researchers increasingly presented their contributions in internationally refereed journals, specialist conferences, edited volumes and public research repositories. The meaning of publication quality varied considerably between fields, especially where conference proceedings served as major outlets for fast-developing computer-science research. Theoretical papers were judged primarily by the originality and correctness of mathematical arguments, whereas experimental systems required persuasive evaluation protocols. The emergence of shared datasets and openly available software made some results easier to scrutinise and replicate beyond the authors' institutions. This development also increased the importance of responsible data collection, clear licensing and transparent reporting of experimental conditions. Research evaluation remained imperfect because citation totals and publication counts cannot measure every form of conceptual or engineering originality. A significant algorithm may become influential only after later adaptations, while an experimental demonstrator may receive attention without establishing a durable scientific advance. For this reason, the achievements of the Prague school require analysis through the substance of identifiable results and their reception in relevant international communities. The distinction between scientific contribution and public visibility is especially important when universities describe their performance to prospective students or external partners.

European integration strengthened the institutional environment in which Prague's computer-science communities operated, particularly after Czech accession to the European Union in

2004. Participation in multinational programmes provided opportunities for joint experiments, research mobility, specialist equipment and shared digital resources. International grants also required increasingly professional coordination of research objectives, partner responsibilities and financial reporting. These arrangements could enable research groups to undertake projects whose scale exceeded the resources of a single national institution. However, joining a consortium did not by itself demonstrate an original Czech contribution to the project's scientific findings. The contribution must be established through research outputs, technical responsibilities and substantive participation in published work. The European context also encouraged the formation of collaborations that joined theoretical informatics, software engineering, language technology and applied artificial intelligence. Czech universities benefited when such projects supported durable expertise rather than only temporary project administration or narrowly defined deliverables. The strongest forms of integration were those in which Prague researchers participated in shaping scientific questions as well as implementing agreed tasks.

Industrial collaboration was another characteristic of the Prague research ecosystem, although its meaning differed across scientific fields. Research on databases and software systems could support commercial information platforms, while computer vision and robotics interacted with manufacturing and automation. Artificial-intelligence teams considered transport, security, logistics and planning problems that required both mathematical reasoning and operational understanding. Technology transfer took different forms, including contract research, joint laboratories, employment of graduates, licensing and the establishment of new enterprises. Not every collaboration produced a marketable product, and an industrial contract should not automatically be classified as a scientific breakthrough. Conversely, the absence of immediate revenue did not diminish the importance of fundamental results later used in software systems or engineering methods. A mature research partnership required explicit treatment of intellectual property, publication rights, confidential data and the independence of academic evaluation. Prague universities also faced the problem of sustaining open scientific communication while cooperating with firms that legitimately protected proprietary knowledge. The effectiveness of these relationships depended upon whether scientific questions remained meaningful beyond the immediate needs of the contracting organisation. Institutional cooperation was most effective when researchers could exchange expertise without losing responsibility for the quality of their disciplinary contributions. Such conditions turned international partnership into a means of developing scientific capacity rather than merely obtaining additional external funding.

The emergence of prg.ai in 2019 marked a more explicit effort to coordinate the capital's research and innovation environment around artificial intelligence. The initiative was established by researchers associated with the Czech Technical University, Charles University and the Czech Academy of Sciences, with involvement from the City of Prague. Its purpose was to strengthen connections among academic research, education, companies and the wider public rather than to create another specialised university department. The initiative therefore represented an organisational response to the fragmented geography of expertise that had developed through earlier decades. Activities concerning talent, international promotion and the responsible understanding of artificial intelligence contributed to the visibility of the Prague ecosystem. The

organisation should not be confused with a direct producer of all the research outputs generated by its participating institutions. Its possible contribution lay in improving conditions for collaboration, attracting specialists and helping external partners identify available expertise. The establishment of prg.ai also illustrates the growing importance of city-level innovation policy alongside national research governance and university autonomy. By 2025, such networks had become part of the institutional environment through which Prague sought a recognised role in European artificial-intelligence research. The longer-term effectiveness of this approach depended upon measurable cooperation and durable scientific capacity rather than branding alone.

Prague's computing research also developed through relationships with the institutes of the Czech Academy of Sciences located in the metropolitan area. The Institute of Computer Science and the Institute of Information Theory and Automation contributed expertise in logic, statistical modelling, optimisation, control and related computational fields. Researchers moved between universities and Academy institutes through collaborative publications, grants, seminars and professional appointments. Such interaction helped maintain continuity in specialised areas whose long-term research horizons did not always correspond to industrial development cycles. It also created opportunities for complementary institutional arrangements, since some investigators concentrated on fundamental questions while others balanced teaching with research. The resulting ecosystem was not a unified organisation, and overlapping research agendas sometimes required careful coordination. Nevertheless, cross-institutional collaboration encouraged scientific problems to circulate beyond administrative boundaries and helped smaller groups reach international partners. Prague’s distinctiveness should therefore be understood as the concentration of interconnected research environments rather than the dominance of one university. This wider setting provided conditions for the development of knowledge that could later be applied in many parts of the Czech economy.

The changing balance between fundamental research and application became especially apparent during the final decade covered by this study. Artificial intelligence, robotic perception and distributed software increasingly attracted public attention because they were associated with strategic technological transformation. At the same time, the mathematical foundations of algorithms, formal methods and linguistic representation remained necessary for evaluating the trustworthiness of new systems. Large datasets and powerful computing resources altered the feasibility of experiments but did not eliminate the need for sound research design. The ability to compare alternative methods and to identify uncertainty became important as predictive models were used in practical environments. Prague researchers participated in these trends from different institutional starting points, producing a diversity of research approaches rather than one unified school of thought. Their contributions also reflected international collaborations in which affiliation and individual intellectual responsibility could not always be reduced to national categories. A sound historical account must therefore distinguish original Czech-developed methods, collaborative international publications and the local deployment of technologies created elsewhere. It must similarly avoid treating aspirations expressed in strategic documents as accomplished scientific results by the endpoint of 2025. Scientific depth remained essential

even when public narratives emphasised technological novelty over the gradual development of research methods.

Several structural constraints accompanied the expansion of Prague's computer-science institutions after independence. Specialised research groups required stable long-term support, while competitive grants tended to finance projects with defined milestones and limited durations. The rising cost of advanced computing resources and the international labour market placed additional pressure upon institutional budgets and recruitment. Some disciplines benefited from substantial experimental infrastructure, whereas theoretical groups often depended more heavily on personnel and uninterrupted research time. Research visibility also remained uneven across fields because commercial applications and demonstrable robotics attracted greater public attention than specialised mathematical advances. Different academic cultures could make interdisciplinary projects difficult when they disagreed about publication practices, research timelines or criteria of scientific success. These tensions required policies that preserved institutional independence while facilitating responsible cooperation with external partners. The history of Prague computing research is therefore not a narrative of uninterrupted expansion but a record of adaptation under financial, organisational and intellectual constraints. Understanding such limits provides a more credible assessment of the achievements attained by 2025 than celebratory descriptions alone.

By the end of 2025, Prague possessed a diversified computer-science ecosystem combining established mathematical scholarship, language technology and advanced engineering informatics. Charles University contributed sustained work in graph theory, computational complexity, software systems, mathematical logic and the computational analysis of language. The Czech Technical University provided a particularly visible environment for computer vision, machine intelligence, autonomous robotics and the engineering of complex computational systems. Institutes and centres such as DIMATIA, the Computer Science Institute, the Center for Machine Perception, the Artificial Intelligence Center and CIIRC illustrate successive forms of organisational specialisation. Individual scholars and research teams gained international visibility through identifiable contributions rather than the mere fact of belonging to historically prestigious universities. European cooperation and local technology partnerships enlarged the range of scientific questions that could be investigated, while also introducing new demands on research management. The coexistence of foundational and applied approaches was a strength because it made specialised knowledge available for interdisciplinary problems without erasing disciplinary distinctions. That diversity also created the obligation to evaluate results with standards appropriate to each scientific field and its methods. The Prague school consequently demonstrates how scientific continuity can become an instrument of innovation when institutions sustain intellectual autonomy, generational renewal and international cooperation. Its history offers a central case for understanding the broader development of Czech information technology between 1993 and 2025.

Brno Information Technology and Cybersecurity School: Masaryk University, Brno University of Technology and the Regional Digital Ecosystem

The emergence of Brno as a major centre of Czech information technology cannot be explained solely by the arrival of international software companies after the political transformation of 1989. Its scientific profile was formed through university teaching, mathematical inquiry, engineering practice and the gradual development of specialised research communities. The independent Czech Republic inherited institutions whose expertise in automated computing, electronics and information processing had accumulated during the Czechoslovak period. After 1993, these inherited capacities entered a substantially different environment of institutional autonomy, international competition and increasingly diversified technological demand. Masaryk University and Brno University of Technology became complementary rather than interchangeable pillars of this transformation, combining distinct approaches to scientific education and research. The former cultivated a broad spectrum of fundamental informatics, mathematical methods, cybersecurity and information systems within a comprehensive university. The latter developed computer engineering, speech technologies, formal verification, digital hardware and industrially oriented research through its technical faculties. Their interaction with regional innovation organisations and private enterprises gradually gave Brno a research ecosystem extending beyond individual departments. The central historical question is therefore how university scholarship became connected with technological entrepreneurship without losing its capacity to produce independent scientific knowledge.

The deeper origins of this ecosystem lie in the long development of technical education in Brno and the earlier institutional history of Masaryk University. Computing in the Czechoslovak period was frequently organised within departments of mathematics, electrical engineering, automation or applied scientific services rather than independent faculties. At Brno University of Technology, the Department of Automatic Computers was established within the electrical-engineering tradition in 1964. Its teaching and research gradually encompassed electronic computing machinery, programming and the design of computational systems under changing technological conditions. At Masaryk University, the Institute of Computer Science originated in 1979 and subsequently acquired an independent position within the university's organisational framework. These units preserved professional skills and technical resources despite the constraints placed on research by the socialist economy and political system. They also demonstrated that informatics was developing as an intellectually distinctive field before Czech independence was established. The democratic changes beginning in 1989 expanded scientific contacts, scholarly mobility and opportunities to reconsider inherited arrangements. The subsequent emergence of specialised informatics faculties thus represented institutional recognition of existing expertise rather than the sudden invention of a new discipline. This distinction is necessary when assessing continuity between the Czechoslovak research tradition and modern Brno computer science.

A decisive institutional development occurred in 1994 with the establishment of the Faculty of Informatics at Masaryk University. The faculty emerged from informatics teaching and research previously organised within the Faculty of Science, reflecting growing demand for disciplinary

autonomy. It was the first independently constituted faculty devoted specifically to informatics in the Czech Republic and consequently acquired importance beyond the region. Jiří Zlatuška served as its founding dean, helping to define a programme that combined mathematical foundations with rapidly expanding technological specialisms. The institution began with a comparatively small community of academics and students, making the subsequent development of research laboratories especially consequential. Its 1996 relocation to Botanická Street placed the faculty in premises more suitable for specialised teaching and the gradual expansion of research activity. The new faculty created opportunities to recruit doctoral students, coordinate advanced seminars and establish stronger relationships with foreign universities. At the same time, it maintained close links with the Institute of Computer Science, whose operational and research functions remained distinct. By the end of the 1990s, Masaryk University's informatics community had become an increasingly visible participant in the national development of computer science.

Brno University of Technology followed a different institutional trajectory that reflected its established commitment to engineering disciplines and industrial applications. The Department of Computer Science and Engineering inherited a substantial background in the design and use of digital computing systems. Following the restructuring of technical education in the 1990s, its research and teaching responsibilities became increasingly difficult to accommodate within existing administrative arrangements. The Faculty of Electrical Engineering and Computer Science had already provided a transitional institutional setting after the university reforms of 1993. On 1 January 2002, the Faculty of Information Technology was formally established as a separate faculty of Brno University of Technology. Its educational programmes joined computer architectures, software engineering, information processing and specialised engineering methods in a coherent academic structure. This distinction from Masaryk University's development matters because industrial computing requires close attention to physical devices and implementable system architectures. Independent faculty status also increased the opportunities for international project participation, strategic recruitment and cooperation with engineering companies. Together, the two university developments created a durable academic framework for the diversification of information-technology research in Brno. They also supplied the region with complementary educational pathways for theoretical specialists, programmers, engineers and applied researchers.

The emergence of two strong faculties did not eliminate the wider institutional contribution of Masaryk University's Institute of Computer Science. Established well before 1993, the institute continued to support university networks, computing facilities, electronic information resources and complex information systems. Its accumulated operational experience provided a setting in which advanced research questions could develop from the practical demands of maintaining dependable digital infrastructure. University information services require expertise in authentication, distributed storage, large-scale computing and organisational interoperability. These tasks are technologically demanding, but they should not automatically be equated with original scientific discoveries. Their scholarly significance becomes clearer where infrastructure operators develop new methods, publish results and establish experimental platforms for external researchers. The institute progressively participated in broader Czech academic

computing networks and supported collaborative research requiring substantial digital resources. It also remained closely connected with the training of technical specialists who moved between university services, research projects and commercial employment. Brno's computing development therefore depended upon a division of responsibilities among research-oriented faculties, technical services and shared scientific infrastructures.

The university information system introduced by Masaryk University in March 1999 offers an unusually instructive example of institutionally embedded software innovation. Its development was initiated in late 1998, and initial applications supported academic administration and information concerning courses and publications. Over time, the system became a central platform for the organisation of university teaching, records and communication. This trajectory illustrates how a university can function simultaneously as the developer, operator and demanding user of an evolving software product. Unlike a laboratory prototype, an administrative platform must remain reliable under changing enrolment patterns, legislation and organisational procedures. Its architecture consequently raises questions of database integrity, access control, maintainability and the management of long-lived software systems. The project's importance should not be exaggerated into a claim that all its components represented novel computer-science theory. It nevertheless demonstrates the practical capacity of Brno institutions to produce sophisticated domestic information systems with continuing operational relevance. Such work also created educational opportunities by exposing students and developers to the complexity of real institutional information environments. The case connects academic capability with the wider Czech transition towards digital administration and software-based services.

Formal methods became one of the fields through which Masaryk University's computer-science research acquired a recognisable international profile. Researchers investigated the mathematical representation of computing systems, the analysis of concurrent processes and the conditions under which programs satisfy required properties. Jiří Barnat and collaborators developed methods intended to exploit parallel and distributed computing resources for demanding verification tasks. The DIVINE model checker became a particularly important research platform, evolving from earlier verification approaches towards the analysis of programs written in established systems languages. Its successive versions confronted the difficulty of exploring extensive state spaces while representing realistic program execution. Research on such tools joins theoretical reasoning about correctness with implementation decisions affecting memory consumption, parallel efficiency and diagnostic usefulness. An industrial programmer cannot infer complete program reliability from a successful test run, particularly when concurrency creates rare but consequential execution sequences. Model checking offers a complementary approach by exploring systematically defined possibilities and identifying violations of specified properties. The Brno school therefore contributed to a domain in which rigorous computer science can inform practical software engineering without claiming that verification removes every form of software risk.

The development of the DIVINE project also illustrates how a scientific school changes its methods while preserving a coherent intellectual objective. Early work emphasised distributed exploration of system states, while later approaches addressed implementation-level programs

through compiler infrastructures and verification-oriented runtime environments. The DIVINE 4 research presented in 2017 included an interpreter for low-level virtual machine code and facilities intended to support analysis of actual C and C++ programs. Such developments made it possible to examine software behaviour at a level closer to the source of practical programming errors. The associated ParaDiSe laboratory cultivated expertise in specification, concurrent software, algorithms and scalable verification methods. International publication and the open availability of research tools facilitated scrutiny by specialists beyond the Czech Republic. Research collaborations could therefore test approaches under different assumptions, benchmarks and application requirements. The existence of a distinctive local group did not make model checking a Czech invention, since the field developed through extensive international scholarship. Brno's contribution lay in identifiable implementations, techniques and professional communities that advanced particular branches of this worldwide field. This is the appropriate scale at which the achievements of a specialised national research school should be assessed.

A second field of particular importance at Masaryk University concerned information retrieval and the organisation of complex digital collections. Pavel Zezula and colleagues investigated similarity-based search, where the objective is to retrieve objects according to measurable resemblance rather than exact symbolic equality. This distinction becomes fundamental when collections contain photographs, multimedia recordings, scientific measurements or descriptions that cannot be reduced to conventional database fields. The monograph Similarity Search: The Metric Space Approach, published in 2005, offered a systematic account of the mathematical and computational issues involved. Subsequent work developed the MESSIF framework for implementing and evaluating retrieval strategies over metric and related data spaces. Its research significance lay in combining formal models of distance with indexing, scalability and software architecture. The resulting methods had relevance to multimedia retrieval and other applications involving large collections of heterogeneous objects. Their development shows how an apparently abstract problem about metric spaces can inform the construction of usable information systems. The Brno group consequently contributed to the international study of data-intensive searching through publications and research software rather than exclusively through commercial products.

The broader study of databases, knowledge extraction and information analysis further diversified the academic environment of Brno. Research addressed how complex records could be indexed, retrieved, combined and interpreted under constraints of computational efficiency and uncertain information. These questions became increasingly important as universities, public bodies and enterprises accumulated digital collections far larger than those encountered during the early 1990s. Masaryk University's data-intensive research communities connected foundational algorithms with experimental evaluation on concrete datasets. At Brno University of Technology, research in information and database systems and knowledge technologies developed complementary interests in applied information processing. The coexistence of these groups allowed students to encounter database theory, software engineering and machine-learning methods in different institutional contexts. Scholarly quality depended upon reproducible methods and results rather than upon the commercial size of the datasets used. At

the same time, the ability to analyse real information flows made the region attractive to firms building information products. The subsequent expansion of analytics enterprises should therefore be interpreted as part of a wider skills and knowledge environment, not as the automatic commercialisation of one university discovery. This distinction also guards against treating every industrial use of data as original academic research.

Cryptography and systems security gave Masaryk University another internationally relevant research specialisation. The Centre for Research on Cryptography and Security, established in 2006, brought together advanced teaching and experimental research on the security of digital devices and applications. Under the leadership of Václav Matyáš, the centre developed a profile encompassing authentication, smartcards, usable security and the practical properties of cryptographic implementations. The distinction between mathematical strength and implementation reliability became especially important as cryptography entered mass-produced electronic equipment. A cryptographic algorithm may possess strong theoretical foundations while the device generating its keys exhibits predictable or biased behaviour. Researchers including Petr Švenda and Matúš Nemec examined vulnerabilities that could be established through large-scale analysis of actual public keys. The resulting work demonstrated how measurements, implementation knowledge and mathematical reasoning can reveal weaknesses invisible to ordinary functional testing. Research of this kind requires careful evaluation of what the evidence proves and whether a vulnerability affects a particular class of deployed products. The university environment supported such scrutiny by connecting specialised laboratory techniques with peer-reviewed international scientific communication.

The vulnerability widely known as ROCA became a particularly notable example of security research undertaken within the Brno academic environment. In 2017, a research team associated with Masaryk University reported weaknesses linked to the generation of RSA keys by certain cryptographic software implementations. Their analysis showed how recognisable mathematical structure in public keys could facilitate factorisation attacks against affected keys. The significance of the result concerned a class of real implementations rather than a general defeat of the underlying RSA cryptosystem. It also demonstrated why cryptographic certification and conventional testing cannot substitute entirely for independent investigation of implementation behaviour. The disclosure required coordination with affected organisations and encouraged remediation, replacement of vulnerable credentials and scrutiny of deployed systems. For a relatively small research community, such a result created visibility through the substance of the demonstrated problem rather than through institutional size. It also strengthened educational opportunities by allowing students to study the relationship between theoretical assurances and actual technological risk. The wider lesson was that cybersecurity research becomes socially consequential when rigorous analysis is connected with responsible disclosure and practical correction. Brno's contribution in this case can be traced to identifiable researchers, experimental methods and published findings.

Brno's cybersecurity school developed beyond cryptographic algorithms towards the training of professionals and the study of organisational resilience. Masaryk University began developing the KYPO cyber range environment in 2013 as a platform for realistic exercises in computer and network defence. A cyber range permits controlled reconstruction of network configurations,

incidents and responses without exposing production systems to the same operational risks. Such facilities join virtualisation, infrastructure orchestration, security monitoring and scenario design with research on human decision-making. The open-source release of the KYPO Cyber Range Platform in 2020 widened the possibility of its use by educational and professional institutions. Its scientific value should be evaluated through the methods and findings generated by experimentation, not merely by the existence of the platform. Exercises can nevertheless reveal the limitations of training programmes and support research on the effectiveness of different defensive procedures. The subsequent development of multidisciplinary cybersecurity centres helped connect engineering expertise with law, management and public policy. This integration reflected the increasing importance of digital infrastructure for institutions whose security responsibilities extend beyond individual technical components.

Brno University of Technology contributed a complementary security research tradition grounded in software engineering, communication systems and embedded devices. Its Faculty of Information Technology cultivated groups examining formal analysis, dependable software and technical vulnerabilities in evolving computing environments. Research on program analysis and verification addressed classes of defects that may be difficult to detect through conventional debugging or ordinary quality assurance. Security-oriented work also investigated network communication, digital forensics and the practical consequences of interactions between software and hardware. These directions created opportunities for joint supervision, industrial assignments and international research projects. They should not be merged without distinction into the work of Masaryk University's cryptography laboratory, since each group pursued different questions and methods. The technological proximity of both universities nonetheless enabled the circulation of specialists familiar with mathematics, programming and operational security. This shared regional competence contributed to the attractiveness of Brno for security enterprises and public institutions. The most durable institutional achievement was the cultivation of different, mutually reinforcing forms of expertise rather than a single centralised school. By 2025, cybersecurity had become a significant bridge between academic research, professional training and the regional software economy.

Speech processing became one of the most internationally visible technological research fields developed at Brno University of Technology. The BUT Speech@FIT group brought together expertise in acoustic modelling, automatic speech recognition, speaker identification and the analysis of spoken language. Its work was associated particularly with Jan Černocký and Lukáš Burget, alongside researchers and students participating in internationally connected projects. Speech recognition is a demanding computational problem because everyday recordings contain variation in accent, channel quality, speaking style and background noise. Early approaches required careful statistical modelling and the extraction of informative acoustic features, while later systems increasingly relied upon neural representations. The Brno group contributed to international evaluations and collaborative research on speech and language technologies during the 2000s. A language-identification system developed in 2005 provides evidence of work progressing from conceptual methods towards tested technological implementation. The group also explored indexing and search in speech recordings, making spoken information more accessible to systematic retrieval. Its achievements illustrate how an engineering-oriented

university could make substantive contributions to information processing at the interface of signal analysis and computer science.

The international significance of the Brno speech school is also visible in the professional development of researchers who subsequently worked across national and institutional boundaries. Tomáš Mikolov completed doctoral research associated with the Brno speech environment before participating in influential language-modelling developments internationally. His later work on neural language representations should not automatically be attributed to experiments or institutional resources located in Brno. The more historically accurate interpretation recognises the training environment while identifying the organisations and collaborators involved in subsequent publications. Similarly, collaborative research in speech recognition often involved participants from several countries with distinct roles in algorithm design and evaluation. Brno's faculty could contribute techniques, datasets, engineering expertise and doctoral supervision without claiming exclusive ownership of the entire research field. The resulting movement of people strengthened scientific contacts between the city and major international laboratories. It also created a channel through which newly developed methods could influence local teaching and future research questions. The wider history demonstrates that a scientific school’s impact may be reflected in intellectual formation and sustained collaboration as well as in publications originating locally. Such distinctions are essential when evaluating national achievements in globally distributed artificial-intelligence research.

Computer graphics, multimedia analysis and human–computer interaction formed another important field of differentiation within Brno's academic environment. At Masaryk University, the Human–Computer Interaction Laboratory was founded in 2002 under the initiative of Jiří Sochor. Its research subsequently examined the design and evaluation of interfaces, immersive environments, visual representations and interactions using novel devices. These studies require more than graphical sophistication because systems must accommodate human perception, cognitive limitations and the conditions of actual use. Laboratory investigation can combine algorithmic development with user observation, comparative testing and domain-specific applications. Brno University of Technology developed complementary capabilities in computer graphics, image processing, multimedia systems and computational photography. Its engineering orientation supported work on efficient implementation and the interaction between algorithms and computing hardware. The presence of different research settings encouraged links with games, cultural applications, industrial visualisation and scientific software. This diversity also demonstrates why computer science cannot be represented adequately by artificial intelligence or cybersecurity alone.

Visual analytics acquired particular significance where computing methods were applied to complex scientific evidence. Masaryk University’s Data Visualization Laboratory, associated with Barbora Kozlíková, investigated visual representations for fields including biochemistry, medicine and security. The challenge was not simply to display increasing quantities of data, but to produce representations that preserved important relationships and supported valid interpretation. A visually attractive image may conceal uncertainty, exaggerate patterns or encourage conclusions not supported by the underlying measurements. Research therefore

included choices about visual encodings, interaction, comparative tasks and the perceptual constraints of different audiences. The laboratory's international cooperation placed local investigations within wider conversations about the design and evaluation of scientific visualisation. Its work also created opportunities for students to connect programming and graphics with problems formulated by specialists in other disciplines. Such interdisciplinarity can generate new algorithms or evaluation methods, although not every successful visualisation constitutes an independent theoretical breakthrough. The Brno experience illustrates how a research laboratory may contribute through both methodological innovation and the careful adaptation of technology to scientific practice. It also strengthened the role of computer science as an enabling discipline for research conducted throughout a comprehensive university.

The interaction between computer science and medicine developed through additional work on biomedical images, data handling and reproducible scientific analysis. Masaryk University’s research environment brought computing specialists into contact with biologists, medical faculties and institutions requiring large-scale information processing. Digital microscopy and medical imaging produce datasets that can be difficult to process reliably without specialised algorithms and computing infrastructure. Researchers including Michal Kozubek investigated methods for image acquisition, analysis and the treatment of noise or optical imperfections. Such work requires awareness of the physical origins of images as well as the computational techniques used to interpret them. Brno’s academic infrastructure supported collaborative projects involving medical visual data and secure access to sensitive information. In these settings, data protection and the reproducibility of processing procedures were as important as raw computational performance. The research contribution should therefore be understood in terms of documented methods, validation and the reliability of conclusions derived from images. These collaborations reinforced the role of informatics within an ecosystem that also contained medical science, biological investigation and specialised instrumentation.

The emergence of extensive digital research infrastructure created a third organisational layer between specialised university laboratories and national research networks. The CERIT-SC scientific cloud developed within Masaryk University's Institute of Computer Science as a resource for computation, storage and technically demanding scientific experiments. Its facilities supported work on large datasets, parallel algorithms, cloud computing and specialised configurations adapted to particular research needs. The establishment of such infrastructure changed what local research groups could investigate without independently purchasing every computing resource. It also encouraged closer attention to reproducibility, access management, technical support and the long-term preservation of scientific information. Computing infrastructure has scientific value when it allows researchers to formulate and evaluate questions that were previously impracticable. Nevertheless, an investment in servers should not be counted as a new algorithm or scientific discovery in its own right. The relevance of CERIT-SC lay in the combination of operational capability, methodological work and services supporting researchers across disciplines. Connections with the wider Czech e-infrastructure also reduced fragmentation between institutions possessing complementary specialised resources. By the end of 2025, this networked mode of operation had become an important characteristic of Czech computational science.

The development of research infrastructure was complemented by efforts to bring innovation-oriented firms into sustained contact with the university environment. At Masaryk University, the Centre for Education, Research and Innovation in Information and Communication Technologies developed a mission involving research projects, industrial cooperation and technology transfer. The associated science park and business-incubation activities offered a setting in which companies could interact with academic specialists and prospective employees. Such proximity may reduce the organisational distance between a research question and a practical technological problem. It does not remove the differences between the objectives of a scientific publication and those of a commercial product. Researchers must still protect methodological independence, while enterprises remain responsible for customers, financing and competitive implementation. The Brno model illustrates how collaboration can be organised through repeated relationships rather than occasional demonstrations of university prototypes. It also highlights the importance of graduate recruitment and professional mobility in the circulation of expertise. The resulting environment linked academic knowledge with software enterprises while preserving diverse forms of institutional responsibility.

The South Moravian Innovation Centre, widely known as JIC, became another essential intermediary in the development of Brno's technology ecosystem. It was established in 2003 through cooperation among the South Moravian Region, the City of Brno and regional universities. Its creation reflected an explicit attempt to strengthen innovative enterprise activity following the economic restructuring of the preceding decade. Rather than functioning as a university department, the centre developed services intended to help entrepreneurs establish companies and improve their business models. Such services included mentoring, connections with experienced founders and support for relationships between research organisations and industry. The regional approach was significant because entrepreneurial development often depends upon access to complementary capabilities rather than one isolated technical invention. University-trained developers might possess valuable programming knowledge while lacking experience of international marketing or company finance. An innovation agency could help address these practical constraints without itself becoming the originator of the scientific knowledge involved. Brno's ecosystem therefore acquired an institutional channel for converting technical competence into sustained entrepreneurial activity. This channel also created conditions in which local successes could support subsequent generations of founders.

Y Soft offers a useful illustration of the movement from local technical initiative towards international enterprise software markets. The company developed in Brno around solutions for managing printing and related document workflows in organisations. Its founder Václav Muchna became associated with the early history of regional start-up support provided through JIC. The significance of this example lies less in the novelty of printing itself than in the development of manageable software services for complex enterprise environments. Such products require reliability, identity management, compatibility with customer systems and extensive attention to deployment and support. These demands employ engineering knowledge acquired in regional educational institutions, even when individual product features are not direct university research outputs. The company's international growth showed that Brno-based teams could develop specialised products for customers beyond the domestic market. It also demonstrated the

economic importance of maintaining a technically strong organisation through successive changes in hardware and business demand. The case provides a model of technology entrepreneurship distinct from mass-market internet platforms or fundamental laboratory research.

The growing role of foreign technology enterprises changed the relationship between regional education and international employment. A significant milestone was the decision of the American open-source software company Red Hat to develop a major engineering centre in Brno. An announcement published by CzechInvest in January 2007 identified the city's technical talent as an important factor in the investment. The centre offered opportunities for local specialists to contribute to software used and reviewed by international development communities. Its significance extended beyond employment because open-source projects involve collaborative testing, documentation and repeated interaction among geographically dispersed teams. Brno graduates could acquire experience of large codebases while participating in a development culture that values public technical scrutiny. At the same time, local academic institutions benefited from professional contacts and the movement of experienced practitioners into teaching or joint projects. The operation of a foreign-owned research and development centre is not identical to the establishment of a domestically owned Czech company. Both types of activity nonetheless contributed to the concentration of engineering expertise within the regional labour market. The relationship shows why ownership, place of development and the nationality of individual researchers should be distinguished in evaluating industrial achievements.

Brno's broader software economy also developed through university-related projects and specialised companies concerned with networks, security and enterprise information. Flowmon Networks provides an example of the commercial development of technologies for understanding and monitoring network traffic. The company grew out of a university-connected project environment and used regional innovation support during its formative stage. Its later acquisition demonstrated how a Czech-founded enterprise could become part of an international commercial structure. The technical content of network monitoring depended upon methods for processing traffic records, identifying patterns and supporting reliable operational decisions. Research expertise could contribute to such methods, although claims of specific invention require evidence about particular algorithms and development teams. Other firms created opportunities for cybersecurity specialists, systems engineers and data analysts trained within local universities. The city consequently developed employment pathways ranging from small research-intensive ventures to established multinational engineering centres. This diversity reduced dependence on any single company while exposing graduates to differing technological and organisational cultures.

The relationship between academic computer science and entrepreneurship was reinforced by doctoral training and participation in international research programmes. Doctoral researchers may specialise in highly abstract questions, but they also acquire methods of experimental design, critical evaluation and technically precise communication. Masaryk University's informatics faculty offered programmes connecting theoretical foundations with a wide range of applied fields. Brno University of Technology contributed research training linked with software systems, communication engineering, multimedia analysis and digital architectures.

International conferences and collaborative grants provided opportunities to exchange ideas with colleagues working in different scientific environments. European funding programmes increased the practical importance of project coordination, research management and cooperation between academic and industrial partners. Students participating in international teams could become familiar with recognised benchmarks and reproducible software practices before entering commercial employment. Conversely, practical problems formulated by enterprises could motivate new university investigations in algorithms, interfaces or dependable systems. The productive relationship did not require research agendas to be subordinated entirely to immediate market demand. Long-term competitiveness depended upon preserving fundamental inquiry while enabling knowledge and people to circulate across institutional boundaries.

A distinctive characteristic of Brno was the breadth of technological activity developing around its university computer-science schools. Alongside software research, the region maintained engineering capabilities in microelectronics, advanced instruments, manufacturing and digital communications. This environment created opportunities for embedded computing specialists whose work connects algorithms with physical devices. Research groups at Brno University of Technology examined dependable digital systems, computer architectures, specialised hardware and automation. Such work illustrates why the boundaries between information technology and conventional electrical engineering remain permeable. Many industrial devices require real-time processing, fault tolerance and reliable interaction with sensors or actuators. These requirements cannot be met solely through general-purpose software architecture without consideration of hardware constraints. Cooperation across technical departments allowed researchers to investigate systems-level problems while drawing upon specialised engineering knowledge. The region’s technological diversity therefore strengthened rather than diluted the distinctive identity of its computer-science research.

Internationalisation changed the scientific culture of both Brno universities throughout the period from 1993 to 2025. Early efforts centred on reconnecting research communities with conferences, visiting appointments and scholarly networks that had previously been difficult to access. European Union membership in 2004 widened the organisational setting for research mobility, collaborative grants and exchanges involving technical personnel. During the following decades, Brno groups increasingly participated in projects whose intellectual and financial structures crossed national borders. Joint publications became important vehicles for demonstrating contributions within fields characterised by rapid methodological change. The international recruitment of researchers also exposed local teams to new techniques and styles of academic argument. At the same time, international competition created pressure to support researchers through stable positions and accessible advanced equipment. Strong publication records alone could not guarantee that doctoral graduates would remain in the region if employment and research conditions were inadequate. Consequently, successful institutional development required attention to professional continuity and the conditions under which scientific schools could reproduce themselves. The interaction between openness and retention became a continuing challenge for a medium-sized European research centre.

The growth of Brno's research and technology ecosystem also produced structural tensions that should not be obscured by accounts of individual successes. Universities were expected to provide high-quality undergraduate education, advanced doctoral supervision and internationally competitive research with finite institutional resources. Industrial partners sought qualified graduates, timely technical results and reliable commercial cooperation, objectives that did not always align with academic research cycles. Large international companies could attract experienced specialists more readily than small university teams with limited salary budgets. Research infrastructures also required continuous expenditure on technical staff, electricity, software maintenance and equipment renewal after initial investments were completed. Smaller ventures faced difficulties in obtaining growth capital, entering foreign markets and protecting technical expertise in negotiations with powerful customers. The concentration of opportunities in a large metropolitan centre could reinforce differences between Brno and less specialised municipalities elsewhere in South Moravia. These pressures do not negate the achievements of the region, but they show why innovation policy must be assessed through long-term institutional capacity. A mature research ecosystem is sustained through the management of competing expectations rather than through the assumption that all stakeholders pursue identical goals.

By the end of 2025, Brno had established a diversified and internationally connected environment for computer-science research and technological enterprise. Masaryk University contributed distinctive strengths in formal verification, cryptographic security, information retrieval, digital infrastructure and interdisciplinary information systems. Brno University of Technology developed internationally visible capabilities in speech processing, software and hardware engineering, multimedia technologies and dependable computing. The Institute of Computer Science and associated research infrastructures provided shared resources connecting specialised investigators with wider national scientific networks. Regional organisations such as JIC helped create practical channels through which technically trained people could establish enterprises or expand existing companies. International corporations and locally founded firms further diversified employment opportunities and exposed engineering teams to global markets. These achievements were cumulative, building upon knowledge accumulated before 1993 while responding to successive technological changes and institutional reforms. They should be evaluated through identifiable publications, technical systems, educational outcomes and durable forms of cooperation rather than unqualified claims of regional superiority. The Brno experience demonstrates how scientific depth, institutional diversity and entrepreneurship can reinforce one another without eliminating their distinctive purposes. It therefore represents an important case of the polycentric development of Czech computer science within the broader European research and innovation landscape.

Ostrava Computational Research School: VSB—Technical University of Ostrava, IT4Innovations and National Supercomputing Development

The Ostrava school of computational research illustrates how an inherited engineering culture can acquire a new scientific identity when computation becomes a central method of inquiry. Between 1993 and 2025, this transformation connected established traditions in mining, mechanical engineering, applied mathematics and industrial automation with modern computer science. Its development cannot be described adequately as the acquisition of several exceptionally powerful computers, because sophisticated equipment produces valuable science only when investigators formulate rigorous problems and methods. VSB—Technical University of Ostrava provided an institutional framework in which numerical mathematics, computer engineering, scientific programming and practical industrial challenges could influence one another. The IT4Innovations National Supercomputing Center subsequently added a national and European dimension to this regional intellectual environment. The central contribution of the emerging research school was the combination of computational infrastructure with expertise in scalable algorithms, complex simulation and data-intensive investigation. This combination enabled research communities from different scientific disciplines to pursue problems requiring resources beyond conventional university laboratories. It also changed Ostrava's place within the geographical organisation of Czech science, adding a specialised centre to those already established in Prague and Brno. An accurate institutional history must therefore explain the relationships between scientific traditions, particular researchers, verifiable publications, infrastructure governance and the wider economic transformation of the region.

The historical roots of this transformation extend to a much earlier period when technical scholarship in the Ostrava region developed around industrial production and the management of complex physical processes. Mining and metallurgy demanded quantitative investigation of materials, machinery, geological structures, transport systems and the behaviour of interconnected industrial operations. Such problems encouraged approaches based on mechanics, mathematical modelling, measurement and systematic optimisation before contemporary digital computing was widely available. As electronic technologies advanced, engineering calculations increasingly became tasks suitable for programmable machines rather than manual numerical procedures. The university’s disciplinary inheritance thus included a practical understanding that mathematical models must be translated into procedures capable of producing reliable results. This inheritance should not be confused with a fully developed school of modern high-performance computing, which emerged under substantially later technological and organisational conditions. Nevertheless, it supplied a reservoir of engineering questions whose numerical complexity could motivate original research into algorithms and software. The shift towards computer-assisted simulation gradually connected theoretical computation with the needs of heavy industry, energy systems and infrastructure design. After the political changes of 1989, these relationships were reconsidered as industrial restructuring altered the regional economy and universities gained wider opportunities for collaboration. The resulting development was cumulative, because new computational techniques were applied to

problems whose intellectual and economic significance had been recognised long before Czech independence.

The institutional position of informatics at Ostrava changed significantly in the years immediately surrounding the establishment of the independent Czech Republic. A separate Faculty of Electrical Engineering emerged at the university in January 1991 from the former combined mechanical and electrical engineering faculty. In September 1993, its name became the Faculty of Electrical Engineering and Computer Science, acknowledging the increasing importance of informatics within engineering education. The change expressed more than an administrative preference, since software, algorithms and information systems were becoming indispensable to modern technical specialisation. Teaching and investigation could now develop around computer science while maintaining close relationships with electronics, control engineering and industrial applications. The university adopted the name VSB—Technical University of Ostrava in 1995, reflecting its broader polytechnical profile. Although individual departments differed in their research capacities, the institution possessed conditions favourable to interaction among mathematics, engineering and computing. This organisation provided opportunities to educate specialists who understood both computational theory and the technical systems that required its application. The events of the early 1990s consequently established an academic foundation for later computational infrastructure investment rather than producing immediate national supercomputing capability.

The contribution of individual academic leaders illustrates how disciplinary institutions were built before major research infrastructure became available. Ivo Vondrák has described his participation in the establishment of the university's computer science department in 1990 and its subsequent development. His academic activity combined computer science education, the organisation of research and later responsibilities in university leadership. Such work matters because a sustainable computational school requires teaching programmes, permanent research groups and the capacity to recruit younger specialists. A computer science department can preserve knowledge in programming, algorithms and systems design even when its immediate material resources remain comparatively limited. Those capabilities provide the human basis for proposing larger projects and engaging with demanding international partners. The professional development of Ostrava's computer scientists also reflected the expanding availability of foreign publications, research visits and scientific conferences after 1989. International exposure widened the range of methodological choices while domestic industrial problems continued to supply strong application-oriented incentives. The establishment of specialised departments therefore connected intellectual continuity with the institutional freedom of the new period. This formative stage helps explain why a major supercomputing centre could emerge through university initiative rather than having to construct all its research expertise from the beginning.

During the 1990s, the university's engineering orientation created opportunities for interdisciplinary computational projects extending across departmental boundaries. Researchers in mechanical engineering and applied mathematics needed numerical procedures for stress analysis, heat transfer, structural mechanics and other complex models. Specialists in electrical engineering investigated computational control, signal processing and the behaviour of

engineered systems. Computer scientists contributed algorithm design, programming methods, data structures and approaches to the organisation of increasingly complex digital systems. The resulting collaborations were not necessarily concentrated within one formal institute, because computational knowledge circulated through departments and shared teaching responsibilities. Their historical importance lay in creating a community able to recognise common methodological challenges beneath apparently unrelated engineering applications. Reliable computation required attention to numerical accuracy, efficient implementation and the interpretation of approximate results, not merely access to faster processors. At the same time, the economic restructuring of the Moravian-Silesian region encouraged greater interest in technological activities capable of diversifying its industrial base. The connection between established engineering expertise and new information technologies became one of the conditions from which the later Ostrava computational research ecosystem developed.

The first decade of the twenty-first century progressively changed the scale at which Ostrava researchers could formulate computational ambitions. The Czech Republic's accession to the European Union in 2004 expanded the institutional context for research cooperation, mobility and infrastructure development. European funding mechanisms created possibilities for investments that would have been difficult to support from conventional departmental budgets. Yet large computing projects required convincing scientific programmes, qualified investigators, operational planning and relationships with prospective users. The university accordingly had to demonstrate that a national facility would serve research communities beyond one city or one engineering discipline. Its proposals drew upon the distinction between owning computing machines and providing an organised scientific service with transparent access conditions. The potential value of shared supercomputing was particularly apparent in computationally intensive problems whose efficient solution depended on specialist software and parallel algorithms. Developments in materials research, numerical simulation and digital engineering simultaneously increased the demand for computing capacity. Regional ambitions could therefore be presented within the wider requirements of Czech research policy rather than as local economic development alone. By the end of the 2000s, the intellectual and administrative foundations were becoming available for a substantially larger research centre.

The decisive institutional breakthrough came in 2011 with approval of a major European-funded project for the creation of IT4Innovations in Ostrava. VSB—Technical University of Ostrava led the initiative together with the University of Ostrava, Silesian University in Opava, Brno University of Technology and the Institute of Geonics of the Czech Academy of Sciences. The consortium demonstrated that the planned centre was intended to support a wider scientific community rather than reproduce a single university department. Its establishment reflected an investment strategy combining facilities, advanced research, technical services and preparation of qualified personnel. The participation of mathematical and geoscientific researchers was especially important because their work presented difficult computational problems suited to parallel methods. University cooperation also broadened possibilities for developing algorithms and transferring knowledge to applied scientific disciplines. European structural support provided the exceptional capital investment, but the long-term value of the centre would depend on research programmes and continuing operations. The project marked a transition from preparatory

institutional development to the systematic construction of national supercomputing capacity. It also made Ostrava a focal point in discussions about the distribution of research infrastructures across the Czech Republic.

The organisational design of IT4Innovations reflected the need to integrate scientific activity with dependable operation of expensive computing systems. As a university institute, the centre belonged to VSB—Technical University of Ostrava while developing a mission extending beyond the university's own research needs. Scientists required access to processors, data storage and specialist software, whereas infrastructure engineers had to maintain operating systems, networks, cooling and equipment reliability. These responsibilities differ from conventional classroom computing or the maintenance of a small departmental server. The research programme therefore had to incorporate professional system administration, allocation procedures, support for users and continuing technical training. Transparent access mechanisms were necessary because demand from different disciplines could exceed the available capacity. A national centre also needed to demonstrate that the allocation of resources was linked to credible scientific objectives rather than institutional prestige. This organisational dimension changed the practical conditions under which Czech scholars could undertake computationally demanding projects. The construction of dedicated infrastructure made it possible to combine centralised equipment provision with distributed scientific authorship. The significance of IT4Innovations thus included new forms of research governance as well as an expanded stock of technological resources.

Research into parallel algorithms became a central means by which the Ostrava school developed an identifiable scientific profile. Parallel computing requires the division of a computational problem into tasks that can proceed simultaneously while exchanging information when necessary. The efficiency of this approach depends upon the structure of the problem, the balance between tasks and the communication costs of a particular computing architecture. Increasing the number of processors does not automatically produce an equivalent reduction in calculation time. Researchers therefore investigate decomposition, memory locality, synchronisation and numerical stability as independent scientific problems. Such questions are particularly demanding in large systems of equations arising from engineering models with millions of unknown quantities. Ostrava teams developed expertise in approaches that connect mathematical analysis with detailed knowledge of hardware behaviour. The research environment supported collaborations among mathematicians, software specialists and engineers concerned with practical numerical applications. The resulting knowledge was essential for turning nominal machine performance into reliable and reproducible scientific computation.

The installation of the Anselm supercomputer in 2013 established the first operational stage of the new national facility. Its approximate theoretical performance of ninety-four teraflops represented a substantial resource for the Czech research community at the time. The centre's dedicated building opened in 2014, giving the project a specialised physical and organisational base for future expansion. Although Anselm's numerical capacity would later appear modest, its introduction made advanced parallel computation accessible to users who lacked comparable resources locally. Early operating experience also allowed technical staff to refine scheduling,

monitoring, data management and user support procedures. Investigators gained opportunities to test algorithms against real multiprocessor architectures rather than relying exclusively on local workstations or theoretical performance assumptions. Such testing can reveal communication bottlenecks and memory limitations that remain invisible in small numerical experiments. The machine's historical role therefore includes the development of user communities and institutional competence alongside its measurable processing capability. It also helped establish a culture of competitive resource allocation and specialised training that remained relevant as later systems were installed. Anselm should consequently be understood as both a technological milestone and an instrument for building a national practice of shared scientific computing.

A further stage followed in 2015 with the introduction of the Salomon supercomputer, whose theoretical peak performance reached approximately two petaflops. On entering the international TOP500 ranking, the system occupied fortieth place, demonstrating the scale of the new Czech installation in contemporary global terms. Its computing architecture allowed research groups to extend simulations to numerical problems beyond the practical reach of smaller systems. The increase in capacity was especially valuable for models requiring large numbers of parallel processes or extensive memory resources. Nevertheless, international ranking positions describe measured computational performance rather than the originality of individual research projects. The importance of Salomon must therefore also be evaluated through the scientific work that users could undertake and the methods required to exploit its resources. Researchers investigated engineering structures, biological and chemical processes, physical systems and other subjects with high computational demands. The growing diversity of users brought different expectations concerning software environments, computational accuracy and the management of scientific data. Salomon strengthened Ostrava's national research role by providing a shared facility whose usefulness extended far beyond its host university.

The expansion from Anselm to Salomon made questions of system architecture and user demand increasingly important in research planning. Large computing centres must balance the need for powerful conventional processors against specialised architectures designed for particular workloads. Accelerators such as graphics processing units can improve the execution of suitable algorithms, but their effectiveness depends on data transfer and the organisation of software. Scientific programs written for traditional central processing units do not necessarily achieve high performance when transferred to accelerator-based systems without substantial redesign. Storage bandwidth, memory capacity and network latency likewise affect the time required to obtain usable results from large numerical calculations. Ostrava researchers therefore examined performance at the level of complete computational workflows rather than treating processor speed as an isolated objective. This perspective also encouraged the development of tools for testing applications under different combinations of hardware and software. The centre had to maintain technical expertise across changing architectures while preserving continuity for existing research communities. Choices concerning future infrastructure could consequently be informed by observed scientific workloads and systematic performance analysis. The research

implications of hardware development were thus inseparable from the accumulated experience of providing a national user service.

The installation of specialised computing resources in 2019 reflected the growing diversity of scientific workloads at IT4Innovations. A graphics-processor-oriented NVIDIA DGX-2 system was introduced to support calculations especially relevant to artificial intelligence and related data-intensive methods. During the same year, the Barbora supercomputer expanded the centre's general-purpose computational capacity with a theoretical peak performance of approximately 849 teraflops. Barbora was formally inaugurated in October 2019 and represented another stage in the gradual development of the facility. These additions did not make conventional numerical methods obsolete, because engineering simulation and modern machine learning often impose different computational requirements. Instead, the presence of complementary resources improved the centre's ability to match scientific tasks with suitable machine architectures. Researchers could investigate the performance of algorithms under different arrangements of processors, accelerators and memory resources. This flexibility also benefited users developing increasingly complex workflows linking simulation, data analysis and visualisation. By the end of the decade, Ostrava had become a multi-system computing environment rather than a laboratory organised around one supercomputer.

The use of the national supercomputing infrastructure depended upon procedures enabling scientific groups from different institutions to obtain resources. Open-access competitions allowed researchers to submit projects specifying their objectives, numerical methods and estimated computational requirements. Assessment and allocation procedures were necessary because large-scale processing time is a scarce resource even at a technologically advanced centre. A proposed simulation may demand millions of processor-core hours and substantial storage for intermediate and final results. Expert review should therefore consider both the scientific quality of the investigation and the credibility of its computational plan. Researchers also require access to documentation and technical assistance because ineffective implementation can waste valuable resources regardless of scientific importance. Technical personnel support users with software installations, parallel execution, job scheduling and diagnosis of performance problems. Such services enable smaller teams to undertake investigations that would otherwise require expensive local equipment and specialised administration. The national role of IT4Innovations consequently rests on shared access and professional support as much as on the presence of advanced computing machinery. This infrastructure model illustrates how public scientific investment can extend research opportunities beyond the institution that physically hosts the equipment.

The commissioning of Karolina in 2021 marked a further increase in Ostrava's position within the European supercomputing landscape. Co-financed through the European High Performance Computing Joint Undertaking, the system offered a theoretical peak performance of approximately 15.7 petaflops. It entered the TOP500 ranking in sixty-ninth position in the year of its installation, providing a widely recognised indication of its computational scale. The acquisition illustrated the transition from exclusively national infrastructure development towards joint European investment and access arrangements. Karolina supported researchers requiring large-scale processing for simulation, analysis and emerging artificial intelligence

workloads. Its significance extended to the integration of different hardware components and the management of complex computational environments. The retirement of Anselm and Salomon in 2021 demonstrated that such infrastructure develops through replacement and reconfiguration rather than uninterrupted accumulation of old machines. Long-term research planning therefore required the migration of applications and users to modern systems without unnecessary disruption of scientific activity. Karolina gave the Ostrava school a platform for deeper cooperation with advanced European research networks while retaining its national service mission.

The increasing diversity of computing systems made efficient management of computational jobs a research concern in its own right. Large user communities submit tasks that differ in processing time, memory demands, input data and the suitability of specialised accelerators. A scheduler must allocate available resources while respecting operational constraints and reducing unnecessary periods of inactivity. Poorly configured applications can occupy scarce nodes without yielding a proportional quantity of scientific work. For this reason, performance monitoring, profiling and analysis of computational workloads become important components of research infrastructure. Energy consumption also entered the calculation, because demanding numerical processing requires electricity both for computation and for the cooling of specialised equipment. Reducing the energy needed for a scientifically equivalent result may involve changes in algorithms, hardware utilisation or the organisation of workloads. Comparisons between systems therefore require more careful interpretation than a simple account of advertised processor performance. The research environment at Ostrava increasingly connected software optimisation, operational reliability and environmental responsibility within the broader management of advanced computing resources. Such work demonstrates that a modern computational school studies the conditions of efficient knowledge production as well as the scientific models executed on its machines.

One of the most significant original research directions associated with Ostrava concerns scalable solvers for large systems arising from numerical engineering models. Work by Lubomír Říha, Tomáš Kozubek, Michal Merta, Vít Vondrák and collaborators contributed to the development of the ESPRESO software library. The library implements finite-element techniques and a massively parallel approach based on finite-element tearing and interconnecting methods. Its research significance lies in the treatment of complex computations whose component subproblems can be distributed across many processors. The underlying mathematical methods address issues such as the assembly of global solutions, the treatment of interfaces and efficient numerical convergence. Published investigations reported techniques for improving solver performance through algorithmic redesign and the use of accelerators. They also demonstrated the importance of combining theoretical numerical methods with careful evaluation on large experimental computing systems. Such results constitute identifiable contributions to computational mathematics rather than achievements attributable merely to the purchase of a faster computer. The ESPRESO programme exemplifies the capacity of an Ostrava research group to develop specialised tools with potential relevance to demanding international engineering applications.

The significance of such solver development becomes clearer when the concepts of computational scalability and numerical reliability are considered together. Strong scaling examines how the execution time of a fixed problem changes when more computing resources become available. Weak scaling investigates whether a computational method remains efficient as both problem size and the number of processors increase. Neither form of scaling is determined solely by hardware performance, because numerical algorithms may require expensive communication or synchronisation between tasks. For finite-element models, the partitioning of a structure into subdomains influences both computational work and the mathematical conditions at interfaces. Effective methods seek a balance between decomposing a problem and preserving the accuracy and convergence required by its physical interpretation. The Ostrava investigations of hybrid solvers and accelerator support belong to this broader effort to develop algorithms whose scientific usefulness survives changes in computing scale. A speedup measured on one machine should therefore be interpreted alongside the model, numerical tolerances and reference implementation used in the experiment. The scientific value of the research lies in reproducible methodological advances rather than in impressive but context-free acceleration factors. This distinction is particularly important when analysing the relationship between high-performance computing as a research discipline and its practical use in industrial engineering.

Another distinctive line of research was developed through the PERMON numerical software project associated with VSB—Technical University of Ostrava and the Institute of Geonics of the Czech Academy of Sciences. PERMON combines quadratic programming methods with domain decomposition techniques to address large optimisation and numerical mechanics problems. Its modules include procedures relevant to contact mechanics and certain machine-learning formulations involving support vector machines. The system builds upon established numerical frameworks while extending them with problem-specific methods developed by the research teams. The computational treatment of contact is mathematically demanding because the conditions at the interface between physical bodies may change during deformation. Such models can lead to constrained optimisation problems for which ordinary unconstrained equation solvers are insufficient. Researchers therefore require numerical methods that respect physical constraints while remaining effective when the problem is distributed over many processors. The collaboration between university mathematicians and Academy specialists demonstrates how institutional diversity can support the development of reusable scientific software. PERMON exemplifies a form of innovation centred on mathematical formulation, algorithmic implementation and verification rather than on commercially packaged applications.

The deeper scientific contribution of numerical research at Ostrava also concerns the relationship between mathematical approximation and complex physical reality. Engineering models ordinarily replace continuous phenomena with discrete systems that can be represented and processed by computers. Finite-element methods divide physical domains into smaller elements, while boundary-element approaches use mathematical properties of the governing equations to focus certain calculations on boundaries. The choice between these methods depends upon the physical problem, the geometry and the numerical assumptions that can reasonably be justified. Approaches such as finite-element tearing and interconnecting permit

large calculations to be partitioned among computing nodes. Nevertheless, a numerically converged result does not automatically constitute a valid physical prediction if the underlying model is inadequate. Investigators must distinguish errors introduced by discretisation from limitations caused by uncertain material parameters or simplified boundary conditions. This requirement explains why collaboration among mathematicians, domain scientists and software engineers remains essential even at highly automated facilities. Research software becomes scientifically valuable when its users can understand the assumptions and reliability limits of the results it produces. The mathematical orientation of the Ostrava school therefore provides a necessary counterbalance to accounts of computational innovation focused exclusively on hardware.

Computational modelling of materials and nanoscale phenomena became another important element of the centre's interdisciplinary profile. The investigation of matter at very small scales frequently involves interactions that are difficult to determine experimentally in isolation. Numerical methods can help researchers interpret electronic behaviour, structural properties and the responses of materials under different physical conditions. Such simulations may require substantial processing resources because the number of interacting components and the precision of calculations can be considerable. The Modelling for Nanotechnologies laboratory connected advanced computing with questions originating in materials science, physics and chemistry. Its work illustrates how highly specialised scientific problems can justify the development of general computational methods and improved software workflows. At the same time, the contribution of Ostrava should be distinguished from discoveries made independently in other Czech laboratories using computing resources supplied by the centre. Providing a supercomputer for a materials study is an infrastructure contribution, whereas creating a new numerical model constitutes a different kind of scientific achievement. The distinction makes it possible to evaluate the centre's research and service missions without incorrectly assigning the same discovery to every participating institution.

Applications in engineering, physical science, chemistry and the life sciences demonstrated the broad usefulness of shared computing infrastructure. Computational fluid dynamics can investigate the movement of liquids and gases under conditions that would be expensive or hazardous to reproduce experimentally. Structural mechanics simulations help examine how complex components respond to loads, contact and changes in material properties. Chemical modelling may require extensive calculations of molecular structures and interactions, while biological research increasingly generates large datasets requiring sophisticated analysis. The value of a supercomputing centre lies in enabling suitably prepared research groups to pursue these questions at a scientifically meaningful level of complexity. However, the methodologies used in the disciplines are not interchangeable, and each application requires independent validation against accepted standards of the relevant science. Large-scale computation may support the design of experiments without replacing laboratory observations or theoretical criticism. Ostrava's specialists contributed through computing access, algorithmic advice and research collaborations with investigators who possessed disciplinary expertise. This division of responsibility helped make the centre useful to communities that would not ordinarily describe themselves as computer scientists. The resulting network of applications illustrates the social

and scientific reach of advanced computing while preserving the distinction between original computational methods and discoveries in neighbouring fields.

The Advanced Data Analysis and Simulations laboratory developed research concerned with information-rich models of complex social and environmental processes. Jan Martinovič and colleagues investigated workflows combining data processing, simulation and software services relevant to practical decision-making. The Floreon+ system provides a particularly instructive example through its integration of information and modelling for crisis-management applications. Its development has included hydrological situations, traffic conditions and other phenomena whose interpretation requires heterogeneous data and specialised computational procedures. A decision-support system of this kind must combine incoming observations, modelling results and accessible representations of uncertainty. Reliable operation therefore depends upon information integration, data quality, computational scheduling and the ability to communicate results intelligibly to users. The original research lies in creating and improving these computational relationships rather than simply displaying pre-existing information on a map. The project's connection to the Moravian-Silesian region further demonstrates how a national computing centre can address locally significant public needs. It also offers a concrete example of interdisciplinary collaboration without suggesting that computer-generated forecasts remove uncertainty from emergency decisions.

International participation became especially visible when IT4Innovations coordinated the LEXIS project, which began in January 2019 under the European Union’s Horizon 2020 programme. The project brought together high-performance computing, cloud services and large-scale data management in a distributed European architecture. Its objective was to make demanding computing resources more usable for research and industrial problems requiring complex data flows. Participating organisations investigated workflows that could extend across geographically separated facilities rather than remain confined to one computing centre. The project's application areas included aviation-related engineering, meteorological and climate investigations, and hazards associated with earthquakes or tsunamis. These examples show that the organisation of computational workflows can be as difficult as the execution of an individual numerical algorithm. Researchers must coordinate access permissions, data transfer, processing stages and the reproducibility of results across different technological environments. LEXIS also demonstrated that Ostrava could lead a multinational research consortium instead of participating solely as a user of external facilities. The achievement should be understood as a contribution to distributed scientific infrastructure and workflow methods, distinct from the scientific discoveries made through particular simulations. Its development strengthened the centre's experience in combining numerical research with European project management and international software collaboration.

The EXA4MIND project, launched in 2023 under Horizon Europe with coordination from Ostrava, extended this infrastructure-oriented research towards extreme-scale data analysis. Its title refers to extreme analytics for mining data spaces and identifies the challenge of managing large datasets across different computational environments. The project sought to connect storage systems, data management and powerful computing resources while reducing unnecessary administrative and technical barriers. Such work addresses a growing difficulty in modern

science, where the transfer and organisation of data may become as demanding as the calculation itself. Efficient data staging, scheduling and interoperability are consequently research concerns rather than secondary operational details. The consortium included research organisations and industrial partners from several European countries, illustrating the transnational character of emerging data infrastructures. For Ostrava, participation at the coordinating level provided opportunities to develop expertise in the organisation of shared data-intensive scientific processes. The project was active within the 2023–2025 period considered here, and outcomes extending beyond the end of 2025 must not be projected backwards. Its significance within the book therefore lies in the research agenda and cooperation established during the period, rather than in claims concerning achievements realised at a later date.

The formation of e-INFRA CZ further connected Ostrava with national systems for communication, storage and distributed computing. This strategic research infrastructure brings together IT4Innovations, CESNET and the CERIT-SC computing environment associated with Masaryk University. Its organisational model recognises that advanced research requires reliable pathways for transferring information as well as facilities for processing and preserving it. A scientist may need to move observations from a remote laboratory to a computing centre before returning large results to collaborators at another institution. Authentication, network capacity, data integrity and storage management must operate together if this process is to remain practical and trustworthy. The partners have complementary responsibilities, because a national research network and a supercomputing centre are not interchangeable institutions. Joint coordination makes it possible to develop more integrated services while maintaining specialisation within the participating organisations. For Ostrava, e-INFRA CZ strengthened its position as one component of a distributed national research ecosystem rather than an isolated technological facility. The arrangement also demonstrates how a medium-sized country can improve scientific capacity through coordinated infrastructure instead of attempting to duplicate every service in one location. Its value depends upon continuing interoperability, dependable funding and the ability of institutions to respond to changing scientific demands.

Participation in European supercomputing initiatives transformed the international position of Ostrava during the 2010s and early 2020s. The centre developed relationships with programmes and organisations concerned with scientific computing, including PRACE and later the EuroHPC framework. These connections supported shared access, technical exchange and the development of skills applicable across national computing facilities. The European model combines specialised national centres with jointly financed systems and collaborative scientific programmes. Ostrava’s participation in the LUMI consortium exemplified this approach by connecting Czech researchers to a major system located in Kajaani, Finland. This relationship did not mean that LUMI was physically operated in Ostrava or belonged exclusively to the Czech Republic. Rather, Czech participation contributed to a shared European arrangement through which national research communities could obtain access to advanced computational capacity. The distinction between hosting and participating in an infrastructure is essential for an accurate account of national technological development. By 2025, Ostrava had become both a national provider of supercomputing services and an active participant in the governance and use of internationally distributed computational resources.

The development of relationships with industry added a further dimension to the scientific mission of IT4Innovations. Industrial companies may possess technical problems that require extensive simulation or data analysis but lack experience with specialised supercomputing systems. Cooperation can therefore involve feasibility studies, expert consultation, adapted software, jointly designed research projects and training for company personnel. Such activities are more useful when they connect academic expertise with well-defined engineering or business questions than when they promise unspecified technological transformation. The European Digital Innovation Hub Ostrava, established in 2022, brought together IT4Innovations, the university's Faculty of Electrical Engineering and Computer Science and the Moravian-Silesian Innovation Centre. Its objectives included helping smaller enterprises and public organisations understand and adopt advanced digital methods. The associated work encompassed computational modelling, data analytics, digital production and specialised professional development. These forms of cooperation linked the university's national research role with the economic transition of its home region. They also required careful evaluation because the successful delivery of a consulting service is not necessarily equivalent to the discovery of a new scientific method. The most sustainable industrial partnerships are those in which practical challenges stimulate original research while companies receive demonstrable technological benefits.

Education and professional continuity were indispensable to the development of the Ostrava computational research school. Advanced supercomputers require specialists in numerical mathematics, parallel programming, computer architecture, software engineering, data science and systems administration. The university's research and teaching programmes provided pathways through which students could enter this demanding professional environment. Doctoral research allowed young investigators to address unresolved numerical or computational problems under the supervision of experienced scientists. Specialised courses and practical training helped external researchers learn how to make effective use of shared computing facilities. Participation in European educational programmes further exposed students to different hardware architectures, research cultures and performance-analysis methods. Yet the retention of skilled specialists remained a challenge because comparable expertise was also attractive to international companies and better-funded research institutions. Long-term quality depended upon the ability to sustain research groups and offer credible opportunities for early-career development beyond a single grant cycle. The centre's educational contribution therefore formed part of the scientific infrastructure itself, rather than being an optional activity associated with technological publicity.

The installation and ceremonial inauguration of the VLQ quantum computer in Ostrava in September 2025 marked a new technological boundary for the centre. The project was developed through the international LUMI-Q consortium and connected Czech participation with the emerging European quantum computing infrastructure. Its significance differs from the straightforward addition of more conventional processors, because quantum computation relies upon distinct physical and algorithmic principles. Potential applications depend upon specialised quantum algorithms, error-aware methods and the development of suitable interfaces between quantum devices and classical computing systems. The presence of a

quantum machine did not establish that ordinary supercomputing could immediately be replaced or that commercially useful quantum advantage had already been achieved. It instead created a setting for experimental work and for the gradual development of hybrid computational expertise. By the close of 2025, Ostrava had thus acquired a combination of classical supercomputing infrastructure, data-oriented research capabilities and a newly inaugurated quantum platform. Important challenges remained in long-term financing, energy efficiency, access provision, software portability and the interpretation of emerging technologies. The strongest evidence of the Ostrava school's development lies in its identifiable algorithms, research publications, education programmes and durable international partnerships rather than in the novelty of any single machine. Across 1993–2025, this cumulative transformation made Ostrava an important component of Czech computer science and a distinctive participant in the European computational research ecosystem.

The Czech Academy of Sciences and Regional Computer Science Schools: Fundamental Research, Interdisciplinary Methods and Scientific Continuity

The development of computer science in the Czech Republic cannot be understood exclusively through the universities of Prague, Brno and Ostrava, because specialised Academy institutes and smaller regional departments maintained essential strands of research throughout the period from 1993 to 2025. These organisations contributed in different ways, ranging from mathematical logic and stochastic decision theory to spoken-language technology, applied informatics, networked measurement and intelligent industrial control. Their significance lies less in the number of laboratories associated with any single city than in the scientific problems that their researchers were able to formulate and solve. The national research system inherited institutional structures from Czechoslovakia, but its internal relationships changed as democratic academic governance, competitive grants and international publication standards developed. The Czech Academy of Sciences preserved environments dedicated to long-term inquiry, while regional universities increasingly linked specialised research with doctoral training and engineering practice. A balanced history must therefore distinguish the research-centred mission of an Academy institute from the wider educational and regional responsibilities of a university department. It must also distinguish internationally original theoretical contributions from applications of methods developed by the global computer-science community. Such distinctions are particularly important in information technology, where the same word innovation may describe a mathematical theorem, a new software implementation or the successful reorganisation of an institutional service. This chapter examines the institutional communities through which those different achievements became possible, without repeating the detailed technological treatments in earlier chapters. Together, Academy institutes and regional schools reveal a national discipline organised as a network of complementary intellectual specialisations rather than as a hierarchy with one exclusive centre.

The creation of the independent Czech Republic in January 1993 altered the legal and financial arrangements supporting academic research, but did not sever the existing intellectual traditions of informatics and cybernetics. Institutes previously belonging to the Czechoslovak Academy of Sciences entered a successor Academy framework in which professional autonomy and accountability increasingly had to coexist. Mathematicians, computer scientists and control engineers consequently encountered new possibilities for international collaboration alongside increasing expectations concerning publication and grant performance. The change occurred after the political opening of 1989, which had already broadened access to foreign colleagues, academic meetings and technical literature. By the mid-1990s, researchers could more readily form multinational collaborations without abandoning the methodological experience accumulated during earlier decades. Yet the new organisational environment did not automatically provide modern computing facilities, stable project budgets or attractive career prospects for younger specialists. Researchers therefore had to manage the simultaneous demands of institutional adaptation, intellectual renewal and the preservation of established scientific expertise. For computer science, continuity was particularly important in areas where sophisticated proofs, datasets, specialised algorithms and long-running seminars represented valuable resources independent of physical infrastructure. The historical meaning of 1993 is consequently better described as a change in the conditions of scientific inquiry than as the foundation of Czech computer science itself.

The Institute of Computer Science of the Czech Academy of Sciences provides a particularly clear example of this transformation from computational service towards fundamental research. Its institutional history begins in July 1975, when the General Computing Centre was established within the Czechoslovak Academy to provide computing expertise and facilities. The organisation became a scientific institute in November 1980, and during the following decade its activities included programming methods, computer systems and methodological assistance to other research institutes. On 1 January 1993 it adopted the name Institute of Computer Science within the newly organised Czech Academy system, preserving an inherited technical and intellectual base. During the 1990s the emphasis gradually shifted towards independent research into mathematical foundations, computational methods and the principles of information processing. This institutional trajectory matters because an organisation once defined substantially by the provision of computing capacity came increasingly to be assessed by the originality of the knowledge it produced. Its mission also incorporated research infrastructure and collaboration with disciplines that could benefit from advanced computation. The institute became an environment in which theoretical reasoning and data-intensive scientific cooperation could develop without being tied to the curriculum of any single university. The institution's own historical account confirms this evolution and records its further conversion into a public research organisation in 2007. The resulting continuity joined older Academy expertise with the more internationally orientated practices of contemporary computer-science research.

One intellectual foundation of the Institute of Computer Science was the development of mathematical logic, especially the attempt to give rigorous meaning to forms of reasoning involving uncertainty or degrees of truth. Petr Hájek, who directed the institute during the 1990s, played a central role in establishing the international standing of this research direction. His

monograph Metamathematics of Fuzzy Logic, published in 1998, treated many-valued logic as a formal deductive discipline rather than merely a collection of engineering heuristics. The work examined calculi, semantic interpretations and relationships among formal systems, providing a conceptual basis for reasoning about propositions that need not be simply true or false. Its significance arose from the precise mathematical treatment of inference rather than from a claim that fuzzy logic could automatically solve every practical problem involving uncertainty. Such studies connected the Academy tradition in logic with emerging questions in knowledge representation, artificial intelligence and computational reasoning. They also exemplified a form of innovation that produces intellectual tools potentially useful to other disciplines without being itself a marketable software product. Graduate education and international scholarly exchange contributed to the continuation of this tradition, since logical systems develop through publication, criticism and the refinement of proofs. This research line illustrates how a comparatively small specialised institute could participate in international discussions about the foundations of intelligent computation.

The evolution of mathematical fuzzy logic after Hájek also demonstrates that a scientific school is sustained through methodological debate and successive generations rather than the enduring authority of one individual. Researchers associated with the Institute of Computer Science, including Petr Cintula and Zuzana Haniková, contributed to research on non-classical logics, graded truth, algebraic semantics and formal deduction. The Handbook of Mathematical Fuzzy Logic, edited by Cintula, Hájek and Carles Noguera in 2011, provided a substantial synthesis of this international research field. Its role was different from that of an original research article, because a major handbook organises established results and clarifies open questions for specialists entering a complex domain. Nevertheless, such publications can influence the direction of research by establishing reliable terminology and making theoretical connections easier to recognise. The questions addressed by this community also intersect with computer science through formal reasoning about imperfect information and the properties of systems that support machine inference. Their relevance does not depend on the immediate adoption of every logical calculus in commercial artificial-intelligence software. Instead, the school develops standards for evaluating what different inference rules imply and which assumptions are needed for sound reasoning. The Academy’s contemporary description of its theoretical computer-science department continues to identify mathematical logic alongside combinatorics and computational complexity as central research directions. This institutional emphasis demonstrates how foundational inquiry remained important despite the wider technological shift towards data-driven artificial intelligence.

Computational complexity and the mathematical theory of neural computation formed another strand of research within the Institute of Computer Science. The work of Jiří Šíma provides an example of how theoretical questions about artificial neural networks can be investigated independently of their immediate technological popularity. Research on computational models asks what classes of functions or languages can be represented by a specified network architecture and what resources are required to obtain a result. Such questions differ from the practical task of training a model on a dataset, because they concern the limits and formal properties of computation. Šíma's scholarly record includes studies of recurrent networks,

computational power and trade-offs between energy use and processing time. These investigations connected classical theories of automata and complexity with models inspired by neural information processing. They also exposed the need to distinguish abstract idealised models from the engineering constraints of actual devices. Within a national research system, the ability to sustain this work is important because commercial interest in neural networks tends to fluctuate more rapidly than foundational scientific questions. Research groups investigating complexity and discrete structures can therefore preserve intellectual depth while developing concepts that later acquire unexpected relevance. The Institute's continuing interest in combinatorics, mathematical logic and complexity offers an example of such long-term methodological continuity.

Alongside formal research, the Institute of Computer Science developed an interdisciplinary orientation linking statistical modelling and artificial intelligence with other sciences. Its research descriptions identify statistical methods, complex systems and data analysis as fields in which computational concepts support investigations beyond informatics itself. The resulting projects involve questions about how measurements should be interpreted, how models represent uncertainty and how large networks can be analysed without misleading simplifications. In health research, for example, a statistically sophisticated method may be useful only when the sampling process and the meaning of a clinical observation are correctly understood. Environmental investigations similarly require the integration of measurements collected at different scales, often under conditions of missing information or non-stationary behaviour. Computational psychometrics provides another application in which the goal is to analyse measurement and human responses rather than simply maximise algorithmic performance. These collaborations demonstrate that basic informatics can develop through the critical examination of models used in neighbouring disciplines. Such work also creates opportunities for university partners whose subject expertise cannot easily be reproduced within a specialised computing institute. The Institute's own research overview identifies theoretical investigation and interdisciplinary data science as two complementary dimensions of its scientific activity. This combination broadens the meaning of computer-science research without erasing the distinction between a sound computational method and an independently established empirical conclusion.

A second indispensable Academy pillar was the Institute of Information Theory and Automation, whose institutional lineage extends to 1 January 1959. It was created through the combination of a laboratory concerned with automation and telemechanics and a research department devoted to information theory. This origin gave the institute a distinctive orientation towards mathematical models of information, measurement and controlled dynamic behaviour. Its institutional history records internationally recognised work before 1990 on information channels, algebraic control theory, self-adjusting controllers and large distribution networks. The political and economic transformation of the early 1990s therefore encountered a research institution with accumulated competence in both theoretical and application-oriented fields. Unlike a narrowly defined computer-science department, the institute studied how information is used to understand and influence physical, economic or social processes. That mission became increasingly relevant when modern computing enabled more detailed statistical estimation, image processing and algorithmic decision-making. In 2007 the institute became a public research institution, marking

a further stage in the organisational reforms affecting Czech academic science. This long history demonstrates why modern Czech information research cannot be explained entirely through developments in software companies or the expansion of internet infrastructure.

The institutional leadership of Vladimír Kučera illustrates how the Academy tradition in systems science adapted to new scientific conditions during the post-socialist period. Kučera directed the Institute of Information Theory and Automation from 1990 to 1998, encompassing the political opening and the early years of the independent republic. His research in algebraic systems theory, robust control and polynomial methods connected mathematical reasoning with the design of automatic control systems. Papers published during the 1990s addressed such problems as feedback stabilisation, pole placement and the solution of matrix equations arising in control design. The underlying scientific problem is not merely how to automate a machine but how to establish mathematically whether a proposed controller will achieve defined properties. This work is applicable to industrial systems, yet its theoretical methods also belong to the general study of dynamic processes and mathematical optimisation. Institutional leadership in a period of rapid reorganisation required attention to research continuity, international relations and the evolving conditions for scientific careers. The historical account of the institute and Kučera's publication record document the coexistence of these organisational and intellectual contributions. His career also illustrates productive relationships between Academy institutes and technical universities, where advanced control theory is transmitted through research-led teaching. The resulting collaboration helped preserve a distinctive Czech school of mathematical cybernetics during the transformation of scientific governance.

Research on automatic control became increasingly connected with computational modelling as engineered systems grew more complex and expectations of reliability increased. A controller must often operate when observations are noisy, relevant parameters change or external disturbances cannot be predicted in advance. These conditions make the mathematical structure of a model at least as important as the computing hardware used to implement it. Czech research in systems and control consequently investigated methods for analysing stability, estimating system states and determining how control strategies behave under uncertainty. The value of a mathematically justified method lies partly in identifying situations where apparently successful experimental performance does not establish general reliability. Digital implementation also introduces sampling effects, numerical approximation and delays that must be reconciled with continuous descriptions of physical systems. Research institutions capable of maintaining both mathematical and engineering expertise were particularly well placed to address these linked problems. The Institute of Information Theory and Automation provided a setting in which theoretical control and computational techniques could inform one another over many years. This distinction between formal reliability and observed functionality is fundamental to an accurate account of research-based innovation in cybernetics.

Probability and statistical inference represented another major part of the Academy's intellectual contribution to information science. Milan Studený developed a programme investigating conditional independence and the mathematical representation of probabilistic relationships. His monograph Probabilistic Conditional Independence Structures, published by Springer in 2005, offers a rigorous treatment of the structures underlying probabilistic graphical modelling.

The problem is scientifically important because statistical independence assumptions influence how complex dependencies can be represented and how data-based conclusions are interpreted. Conditional independence is not merely a convenient computational shortcut, since an incorrect assumption can change what a model appears to imply about the relationships among variables. Studený's analysis also demonstrates the value of approaches that do not rely exclusively on graphical descriptions, thereby revealing properties that particular diagrams may conceal. These results have relevance to knowledge representation, statistical modelling and certain classes of artificial-intelligence systems. Their original contribution is mathematical rather than the invention of a specific commercial inference product. The 2005 monograph provides identifiable evidence of internationally disseminated research emerging from the Institute of Information Theory and Automation. It exemplifies how a Czech scientific institute could influence the conceptual foundations of information processing through sustained theoretical investigation.

Decision-making under uncertainty became a further characteristic area of the Institute of Information Theory and Automation, notably through the research of Miroslav Kárný and collaborators. The central question concerns how an agent should select actions when the system being controlled is incompletely known and observations provide uncertain evidence. Bayesian identification and adaptive decision strategies offer mathematical approaches for revising beliefs as new information arrives. Kárný's research programme examined fully probabilistic design, the fusion of information and decisions involving more than one participant. The 2006 monograph Optimized Bayesian Dynamic Advising: Theory and Algorithms, written with several collaborators, presents an example of this effort to connect formal probability with computational decision support. Such methods require careful choices about objectives and assumptions, since a formally optimised decision cannot compensate for an inappropriate representation of what matters. Their scientific value includes the ability to expose these assumptions and to examine how recommendations respond to changes in available evidence. Applied problems provide important tests of the theory, but the generality of the mathematical framework remains a separate question. This school therefore occupies an important position between classical cybernetics, probabilistic artificial intelligence and contemporary adaptive computing.

Digital image analysis became one of the internationally visible domains in which Academy researchers combined mathematical originality with applications in different scientific fields. Jan Flusser, Tomáš Suk and Barbara Zitová investigated invariant descriptors that enable an image or object to be recognised despite certain transformations or degradation. Their 2009 book Moments and Moment Invariants in Pattern Recognition and their 2016 study of two- and three-dimensional image analysis brought together techniques developed across many individual investigations. The problem of invariance is fundamental because images captured at different angles, resolutions or physical conditions cannot always be compared through direct pixel correspondence. Analytical moments provide a structured way to extract properties that may remain informative after transformations, although their effectiveness depends upon the imaging process and the assumptions adopted. Research in registration, deconvolution and image fusion complemented these mathematical techniques by addressing the reconstruction and alignment

of imperfect observations. The resulting methodologies found applications in medicine, astronomy, remote sensing and the analysis of cultural objects. These developments were not confined to the creation of convenient visualisation software, because their significance included demonstrable mathematical properties and reproducible computational procedures. Biographical and publication records of the Institute of Information Theory and Automation establish the connection between the authors and this long-term research environment. The work illustrates how specialised signal-processing groups contributed to internationally relevant methods while sustaining cooperation with universities and external scientific users.

Information theory and signal processing also supported work on economic and social systems, where modelling assumptions often carry substantial consequences for decision-making. The Institute of Information Theory and Automation maintained research in econometrics, stochastic processes and the analysis of complex observed signals. In such contexts, measured information may reflect genuine structural change, temporary fluctuations, measurement error or the combined effects of several unobserved influences. Computational tools can help distinguish among these possibilities, but they cannot remove the need for a defensible statistical specification and knowledge of the investigated domain. Methods developed in signal processing may also inspire analytical approaches in finance, environmental observation or biomedical measurement when common mathematical structures are present. The transfer is scientifically productive only when the new application respects differences in data generation and interpretation. Academy research groups therefore had a particular incentive to maintain dialogue with specialists in the fields that supplied empirical questions. This exchange contributed to the wider development of interdisciplinary computer science after 1993, especially as data storage and processing capabilities expanded. The Academy's systems-oriented research consequently formed a bridge between fundamental information theory and the evidence-based analysis of real processes.

The scientific influence of Academy institutes extended beyond their internal research teams through postgraduate supervision, scholarly journals and collaboration with universities. The Institute of Information Theory and Automation has maintained a relationship with the journal Kybernetika, whose first issue appeared in 1965 and which provided a durable channel for work in cybernetics and related mathematical fields. Editorial activity contributes to scientific infrastructure by making specialised research accessible for scrutiny, replication and further theoretical development. Likewise, the publication of internationally distributed monographs allowed Czech research schools to participate in discussions not restricted by national language or institutional boundaries. Collaboration with universities served a different but complementary purpose, enabling doctoral candidates to encounter established investigators and specialised research questions. Such relationships could connect a regional university's practical problems with the more concentrated mathematical expertise of an Academy institute. They also helped maintain research continuity when individual grants ended or university departments changed their organisational structures. Nevertheless, an institutional partnership should not be counted automatically as evidence of an original scientific discovery, because training, access and publication perform different roles within a research system. An accurate account must therefore consider the quality of scholarly contributions as well as the organisational networks that

supported them. In the Czech case, those networks became increasingly international after European Union accession in 2004 while retaining strong connections among domestic institutions.

The University of West Bohemia in Plzeň represents a regional research environment in which computer science developed through close interaction with engineering and cybernetics. Its Faculty of Applied Sciences brought together mathematical training, computational methods and research concerned with intelligent control and communication systems. The Department of Cybernetics describes its work as including systems theory, planning, intelligent classification and human–machine interaction through spoken language. This specialisation reflected both inherited engineering expertise and the growing importance of computational processing for industrial and communication applications. In the 1990s, regional universities faced the challenge of building distinctive research identities while competing with institutions possessing greater national visibility. Concentrating on problems requiring a combination of theoretical understanding and experimental implementation offered one effective response. Plzeň could develop teams concerned with automatic speech recognition, signal processing and control without reproducing every specialism present in Prague. Their development relied upon education and the creation of research opportunities capable of retaining talented graduates within the region. Plzeň therefore illustrates how a regional school can achieve a coherent identity by building expertise around a connected group of computational problems.

Research on Czech-language speech processing became a particularly recognisable contribution of the Plzeň school. Josef Psutka and collaborators worked on methods and resources necessary for developing large-vocabulary speech recognition systems for a morphologically complex language. Their scientific programme required not only algorithms for acoustic modelling but also carefully transcribed speech data and methods for representing the relationship between spoken and written language. A notable example was the Czech Broadcast News corpus, derived from recordings of Czech radio and television material collected around 2000. Speech and transcript resources published through the Linguistic Data Consortium in 2004 made the material available for broader research use. This achievement should be evaluated as research infrastructure and methodological preparation rather than as a claim that a single dataset constitutes a complete speech-recognition breakthrough. The creation of such resources enabled researchers to compare alternative algorithms and improve the reproducibility of experimental findings. It also required cooperation among specialists in signal processing, linguistics, transcription and statistical modelling. The documented publications by Vlasta Radová, Josef Psutka, Luděk Müller, Pavel Ircing, Jindřich Matoušek and collaborators identify the practical scholarly labour behind these resources. Their work demonstrates how regional institutions could contribute to internationally accessible computing research through original language-specific expertise.

Speech-related research in Plzeň also illustrates the broader evolution of computer science from isolated algorithm design towards integrated computational systems. An effective speech interface must combine audio capture, signal analysis, recognition of linguistic units and an assessment of uncertainty about competing interpretations. Each of these stages presents a distinct scientific problem, and improvements in one stage do not guarantee improved

performance of the complete system. Researchers must evaluate results under realistic acoustic conditions, different speakers and changes in the language used by the target population. Czech-language research introduced further methodological challenges associated with rich inflection and a comparatively smaller pool of training material than that available for English. Work on speech synthesis and human–machine communication added questions about intelligibility, naturalness and the design of accessible interfaces. These problems linked computer science with phonetics, applied mathematics, electronics and the study of human communication. Collaborations with outside laboratories contributed to the exchange of methods while preserving the value of locally collected data and national linguistic knowledge. The Plzeň school consequently offers an example of how applied research may remain intellectually distinctive within an internationally shared technological field.

Palacký University Olomouc developed a different profile, with particular strength in the mathematical analysis of uncertain information and the foundations of data interpretation. Its Department of Computer Science brought together logical methods, discrete mathematics, information representation and questions about how vague properties can be represented formally. Radim Bělohlávek emerged as an internationally active scholar in fuzzy logic, formal concept analysis and relational systems. His research examined how collections of objects and attributes can be organised when observations are graded or incomplete rather than simply present or absent. This question is relevant to knowledge representation because real datasets frequently contain degrees of similarity, ambiguity and uncertain relationships. The mathematical challenge is to preserve rigorous reasoning while allowing representations that are more flexible than conventional binary classification. Work undertaken at Olomouc built connections between the theory of ordered structures, database concepts and the design of methods for examining complex datasets. Bělohlávek's academic record documents his development through Czech universities and his participation in international research environments. The regional significance of this school therefore lies in specialised conceptual expertise rather than in a comprehensive local reproduction of all areas of computing. It illustrates how a department outside the country's largest metropolitan centres can generate results addressing foundational questions of worldwide relevance.

The research partnership of Radim Bělohlávek and Vilém Vychodil provides a concrete example of the intellectual content of the Olomouc school. Their 2005 monograph Fuzzy Equational Logic investigated formal reasoning in mathematical systems that accommodate graded relationships. Related papers addressed the interpretation of relational data, the generalisation of database dependencies and logical approaches to uncertain attributes. A conventional relational database describes precisely defined relations, but many real observations involve similarities or degrees of membership that require additional assumptions. The research problem is not solved merely by attaching numerical values to linguistic labels, because formal operations must preserve a coherent interpretation of the information represented. Mathematical analysis helps clarify which inference rules are justified and how alternative representations affect the results of a query or classification. Work on formal concept analysis also contributes methods for discovering hierarchies of properties and associations within data. Such contributions belong simultaneously to mathematical informatics and the theoretical investigation of knowledge

structures. Their work demonstrates the possibility of combining mathematical generality with research questions arising from information systems and data analysis.

The Olomouc research environment also illustrates how the boundaries of a computer-science school can extend beyond administrative departmental structures. Logical models of uncertainty are relevant to mathematics, but they also inform discussions in philosophy, cognitive science and the analysis of information. Similarly, methods for classifying data can support scientific investigations whose substantive questions originate in medicine, biology or the social sciences. Interdisciplinary work may therefore emerge when a specialised computational group offers methods that other researchers can test against their own evidence. Such cooperation increases the reach of a regional school, although it does not mean that every subsequent application should be attributed exclusively to its mathematical origin. An accurate institutional history must consider the difference between a method's theoretical authorship and the diverse international collaborations through which applications are produced. The participation of Olomouc researchers in journals and scholarly networks further demonstrates that national location need not constrain the intellectual circulation of theoretical results. Doctoral teaching and successive research projects helped transmit the school's expertise from one generation to another. At the same time, its specialised orientation made collaboration with wider Czech and European research communities particularly important. The resulting research model is based on depth within selected mathematical questions and openness to interdisciplinary application.

The Technical University of Liberec illustrates a further variant of regional informatics, grounded more directly in mechatronics, embedded computation and engineering measurement. Its Faculty of Mechatronics and Interdisciplinary Studies was established in 1995, during a period when Czech technical universities were redefining their research and teaching missions. The faculty later adopted a name explicitly including informatics, reflecting the growing importance of computational methods within its interdisciplinary programmes. Liberec inherited a strong industrial environment associated with machinery, textiles and manufacturing, where controlled physical systems created practical demands for modelling and instrumentation. Mechatronics itself brings together mechanical design, electronics, measurement and computing rather than treating software as a separate activity added after engineering decisions have been completed. Its development required researchers capable of designing feedback systems and understanding the limitations of sensors and processors operating under physical constraints. The faculty's institutional history confirms that its scientific orientation was intended to cross the boundaries among engineering, mathematics and the natural sciences. This combination gave the university a profile distinct from the more abstract computer-science programmes of some other Czech centres. Liberec consequently represents an important strand of Czech informatics in which computational reasoning developed in direct contact with material systems.

Research institutes within the Liberec faculty illustrate the practical implications of this interdisciplinary orientation. Activities described by the Institute of Mechatronics and Computer Engineering include applied informatics, database systems, computer modelling, electronic systems and automatic process control. Related work addresses robotics, reliability assessment and the evaluation of risk in engineering applications. These fields are linked by a common concern with how information can be collected, processed and used to guide the behaviour of a

physical system. For instance, a robotic installation requires an appropriate control algorithm, but its reliability also depends on sensing errors, timing, mechanical wear and the interaction between software and hardware. Scientific methods are valuable when they enable these sources of uncertainty to be analysed explicitly rather than concealed by apparently successful demonstrations. The faculty's industrial partnerships provided contexts in which researchers could examine the applicability of their models and adapt experimental designs. Such partnerships were particularly important for a region whose economy had a substantial engineering and manufacturing base. The technical orientation did not preclude theoretical work, because effective control and diagnosis depend upon mathematical description and computational efficiency. Liberec therefore demonstrates how applied informatics can become scientifically meaningful through a disciplined relationship between general methods and challenging practical systems.

The University of South Bohemia in České Budějovice represents an additional form of regional development, connecting informatics with environmental sciences and data-intensive research. The university was established in 1991 and gradually expanded its disciplinary range after the creation of the independent Czech Republic. Within its Faculty of Science, an Institute of Applied Informatics was established on 1 January 2009, creating a more recognisable organisational home for computing-related study and investigation. In 2021 the institute was transformed into the Department of Computer Science, illustrating the further institutional consolidation of the subject. Its research profile has included information security, computer simulations, multimedia, long-term electronic archiving, wireless sensor networks and the integration of computing systems. These activities reflect a scientific environment in which biology, ecology, measurement and specialised data resources have considerable practical relevance. The regional context encouraged work on technologies able to support distributed observations and manage data collected across extended periods. Such questions can be technologically complex even when an individual laboratory possesses less infrastructure than a national supercomputing centre. The department’s official account provides a clear chronology of its establishment and subsequent transformation without implying that all its research directions originated simultaneously. České Budějovice thus illustrates the gradual formation of an informatics institution through the needs of neighbouring scientific disciplines.

The connection between applied informatics and biological research in southern Bohemia deserves particular attention because it demonstrates the interdisciplinary role of regional universities. Ecological and biological investigations increasingly depend on electronic observations, reproducible workflows and the responsible preservation of research data. Sensor networks can extend scientific measurement beyond laboratory walls, but they introduce problems involving power consumption, communication interruptions, calibration and the integrity of stored information. Long-term archiving requires stable descriptions of data provenance and technical arrangements that remain intelligible when software platforms are replaced. Research in these areas therefore connects information technology with methodological questions concerning the reliability and continuity of scientific evidence. The Biology Centre of the Czech Academy of Sciences in České Budějovice adds a nearby research environment in which molecular methods, ecological studies and mathematical modelling are

undertaken. The coexistence of a regional university and an Academy biological centre creates opportunities for collaboration, although a geographical relationship alone does not establish that a particular joint project occurred. It is more accurate to identify the complementary expertise that such organisations can bring to data-intensive science. The University of South Bohemia's applied informatics programmes reflect growing attention to data management, information systems and analytical techniques. The regional experience shows that some of the most valuable roles of computer science consist in making other scientific observations more reliable, accessible and reusable.

Zlín provides a further illustration of the relationship between industrial heritage and the institutional development of applied computer science. Tomas Bata University was established in 2001, building upon earlier technical education associated with the region’s manufacturing traditions. Its Faculty of Applied Informatics began operating as an independent faculty on 1 January 2006 after the reorganisation of an existing institutional base in automation and process control. The faculty’s historical account traces those foundations to a department of automation established in 1986, demonstrating continuity across the political and economic transition. Its educational and scientific profile embraced process automation, information systems and security technologies rather than a narrowly defined programme of general computer-science theory. In Zlín, an important research question concerned how computing could be used to model, optimise and control industrial processes under changing conditions. This orientation linked mathematical methods with the realities of production, safety and technological management. It also created opportunities for cooperation with local firms and for the training of specialists able to move between programming and industrial engineering. Its development forms part of the broader national pattern through which regional technical education generated recognisable scientific environments after 1993.

Research connected with the Faculty of Applied Informatics in Zlín included optimisation, mathematical modelling, artificial intelligence and the control of dynamic processes. Its institutional accounts identify work on soft-computing approaches to control and applications in which numerical techniques are used to search for acceptable system behaviour. The research of Ivan Zelinka provides an example of interest in evolutionary computational methods and the modelling of difficult optimisation problems. In evolutionary computation, a search procedure develops candidate solutions through repeated selection and modification rather than relying solely on a closed-form mathematical answer. Such techniques may be attractive for non-linear problems, but their effectiveness depends on careful comparison with other methods and explicit control of computational cost. Industrial applications further require attention to reliability, reproducibility and constraints that may not be visible in idealised benchmark problems. Research teams working in this environment therefore had to reconcile the flexibility of heuristic methods with the demands of engineering verification. Alongside process control, the faculty developed competence in information security and computational systems used within organisations. The wider scientific contribution should be judged by documented algorithms, publications and experimental evidence rather than by the general presence of automation technologies in local firms. Zlín's research orientation illustrates how specialised applied

informatics could strengthen the Czech innovation ecosystem through engineering problems rooted in a regional industrial economy.

The institutional experiences of Plzeň, Olomouc, Liberec, České Budějovice and Zlín demonstrate that Czech computer science developed through several distinct forms of academic specialisation. Plzeň placed particular emphasis on intelligent systems, control and spoken-language processing, whereas Olomouc cultivated rigorous mathematical approaches to uncertain information. Liberec connected informatics with mechatronics and experimental engineering, while České Budějovice strengthened applied computing in a setting closely linked to environmental and biological inquiry. Zlín developed programmes oriented towards industrial automation, optimisation and organisational information systems. These differences should not be interpreted as rigid boundaries, because research groups frequently share methods and participate in broader professional networks. Nor should the presence of a field in a university curriculum be treated automatically as proof of a sustained, internationally recognised research school. The stronger evidence consists in identifiable researchers, original publications, funded projects and the reproduction of expertise through postgraduate education. Smaller institutions can make important contributions when they pursue carefully selected questions and collaborate with partners possessing complementary resources. Regional plurality therefore increased the intellectual and institutional resilience of Czech computer science without eliminating inequalities in funding, visibility and recruitment.

Collaboration among Academy institutes and regional universities became increasingly important as scientific problems required knowledge from several fields and access to shared infrastructures. An Academy group specialising in formal inference might contribute theoretical methods to a university project investigating uncertain data, while engineers could provide practical tests of abstract control models. In turn, regional language or environmental datasets could stimulate methodological questions not apparent within a centrally organised theoretical programme. Such exchanges are valuable precisely because collaboration does not require every participant to possess the same equipment or pursue an identical research agenda. Researcher mobility, joint supervision and conference participation helped connect domestic institutions with the broader European computer-science community. However, collaboration also requires clear intellectual attribution, especially when a publication emerges from researchers employed in different countries or sectors. Academic credit should follow the documented contributions of individuals and groups rather than the prestige associated with an institution's name. A mature national research system must also sustain the less visible activities of maintaining datasets, libraries, software repositories and specialised training. By 2025, these elements formed an interconnected environment in which basic investigation and applied computing could reinforce one another. The regional and Academy experience therefore provides a necessary complement to accounts centred on highly visible technological companies and national computing facilities.

The development of the Czech Academy of Sciences and regional computer-science schools between 1993 and 2025 can ultimately be interpreted as a history of selective continuity and differentiated modernisation. The Institute of Computer Science preserved a long-term commitment to logical and computational foundations while extending its interdisciplinary work in modelling and data analysis. The Institute of Information Theory and Automation maintained

internationally relevant programmes in control, probabilistic reasoning, decision theory and digital signal processing. Regional universities translated distinctive disciplinary inheritances into research profiles shaped by mathematical questions, language resources, engineering systems and the requirements of neighbouring sciences. Not every institution achieved the same international visibility, and the value of its research cannot be inferred simply from its size or from the number of industrial partnerships it announced. The most persuasive achievements are those supported by identifiable publications, clearly formulated methods and research communities capable of maintaining rigorous standards over time. Scientific infrastructure, educational continuity and regional engagement nevertheless remain essential conditions for producing such work, even when they do not themselves constitute original discoveries. Internationalisation strengthened the possibility that these diverse communities could contribute to questions larger than those any single Czech institution could investigate alone. This experience shows how fundamental knowledge and regional technological competence together contributed to the development of modern Czech information technology.

National and European Digital Research Networks: Scientific Infrastructure, Cybersecurity Governance and Innovation Partnerships

The development of digital research networks in the Czech Republic between 1993 and 2025 reveals how scientific institutions came to depend upon shared technical systems that extended far beyond individual campuses. An electronic network could initially be understood primarily as a means of exchanging messages and transferring documents, yet its role expanded as experimental science, modelling and collaborative research generated increasingly demanding information flows. By the later decades, communication links, distributed computing, cloud platforms, data repositories, identity services and cybersecurity arrangements had become interconnected components of scientific infrastructure. This transformation was institutional as well as technical, because services used by many autonomous organisations required transparent rules for access, finance, responsibility and long-term maintenance. Czech universities and the Academy of Sciences created a durable national base, while European partnerships connected that base to wider research communities. The most important achievement was therefore not a single machine or networking protocol but the gradual construction of a trusted environment through which researchers could combine different resources. A distinction must nevertheless be made between building infrastructure, inventing a novel technical method and producing scientific discoveries through use of the infrastructure. Each represents a different form of contribution and requires different evidence in any assessment of national technological progress. This chapter examines the organisations and governance relationships that enabled such contributions without repeating the earlier technical accounts of networking or supercomputing architectures. Its central concern is the movement from separate research facilities towards a coordinated Czech and European digital research ecosystem.

The independent Czech state inherited a rapidly changing scientific communication environment rather than creating national academic networking from the beginning. Czechoslovakia had established an experimental Internet connection in 1991 and was formally connected to the Internet in February 1992 at the Czech Technical University in Prague. The nationwide Czech Educational and Scientific Network (CESNET) academic backbone was launched on 15 June 1993, shortly after the creation of the independent republic. Its initial intercity connections operated at capacities that seem very small by modern standards but were considerable achievements under contemporary financial and telecommunications constraints. The historical importance of these early links lay in opening ordinary channels of electronic communication to universities located in different Czech regions. Their development required practical cooperation between university computing centres, network engineers and academic authorities who could identify shared priorities. Scientific activity benefited from more reliable contact with foreign departments, growing access to electronic information and the circulation of specialised research software. The network's early history also demonstrates why political independence and technological modernisation cannot be treated as identical events, since technical foundations predated the new state. The emerging system established a precedent for treating connectivity as a public research capability rather than a collection of unrelated commercial subscriptions.

A fundamental institutional step followed in 1996 when Czech universities and the Academy of Sciences established the CESNET association to undertake the operation and development of academic networking. Responsibility for the network thereby moved from an arrangement centred on the Czech Technical University to an organisation representing a wider constituency of participating institutions. This governance model was significant because research networks depend upon sustained cooperation among users whose budgets, technological needs and academic missions are not identical. Common management enabled more systematic discussion of future infrastructure investment and the service levels expected by member organisations. The association’s remit gradually expanded from communication links towards data storage, computational access, identity services and research into advanced networking methods. Its trajectory also reflected the broader European movement towards national research and education networks that collaborate across borders while retaining domestic responsibility. Such organisations are neither ordinary telecommunications retailers nor academic departments, since they combine continuing public-service obligations with specialised technological expertise. CESNET's subsequent relationship with the European GÉANT (pan-European research and education network) community placed the Czech model within a federated infrastructure where national organisations support collective international services. Membership did not eliminate the need for domestic investment, but made it possible to share standards, operational knowledge and sophisticated international connectivity. Institutional continuity after 1996 consequently proved just as important as any individual increase in network speed.

The technological development of the academic backbone illustrates the changing scale of Czech research collaboration across three decades. Earlier upgrades replaced low-capacity connections with more capable transport technologies and eventually with a substantial optical

network capable of supporting demanding experiments. The transition involved not only faster physical links but also improved reliability, redundancy, performance monitoring and the management of network traffic. Scientific applications increasingly required predictable transmission characteristics, especially where large datasets could not be moved conveniently by ordinary commercial services. The contemporary CESNET3 backbone represented a further architectural renewal rather than merely the renaming of an unchanged legacy system. During the upgrade completed in 2023, the network gained the ability to support transmission at up to 400 gigabits per second per channel on parts of the backbone. This figure describes a defined network capability and should not be interpreted as the guaranteed transfer rate available to every connected researcher's workstation. End-to-end performance still depends upon access links, storage systems, protocols, congestion, institutional security policies and the characteristics of particular applications. The historical trend demonstrates how an initial service for scientific communication evolved into a platform supporting both scientific experiments and research into communication technologies themselves.

International integration gave this national development a second essential dimension, because Czech researchers increasingly needed dependable connections with scientific facilities and colleagues outside the country. The pan-European GÉANT network provides the cooperative framework through which national research and education networks exchange data and develop common services. Its significance cannot be reduced to a single international circuit, since the partnership also addresses network security, federated identities, advanced services and operational coordination. Czech participation enabled national institutions to join a European technical community capable of confronting problems beyond the resources of an individual university. Cross-border collaboration became particularly important for projects generating data at one facility but analysing them at several geographically separated institutions. The GÉANT approach preserves the distinction between a common European backbone and the national networks that connect researchers to it. This layered arrangement gives countries a degree of autonomy while allowing access to resources that depend upon international scale and collective funding. It also requires agreement on incident handling, acceptable use, identity management and the responsibilities of participating service providers. The GÉANT programme launched its GN5-2 project in January 2025, continuing a research-network agenda combining resilience, connectivity and cross-border collaboration. By the end of the period, Czech academic networking had therefore become a stable component of a European infrastructure rather than an isolated national technical project.

The demands of international experimental science made the practical value of research networking especially visible. Large scientific collaborations often generate data volumes that cannot sensibly be copied through ad hoc arrangements or processed at their point of origin. Czech participation in particle physics, astronomy, structural biology and other data-intensive disciplines consequently increased the importance of dependable transport infrastructure. CESNET's connection to the Large Hadron Collider Open Network Environment in 2013 exemplified this requirement, because it supported the movement of information associated with particle-physics experiments. Such a connection is not itself an experimental discovery, but it enables scientific groups to undertake analyses that would otherwise be hindered by

communication constraints. Laboratories using sophisticated microscopes or sequencing equipment encounter related difficulties when measurements need to be stored and processed at remote facilities. Reliable networks therefore have consequences for research design, influencing whether investigators can collaborate across institutions without duplicating expensive equipment. Their value includes transfer capacity but also predictable access arrangements, monitoring and coordination with computing centres at either end of a data flow. The Czech experience illustrates how scientific participation abroad and technological capacity at home become mutually dependent rather than competing priorities.

Network reliability gradually became an important area of research infrastructure governance, since a faster service is not necessarily a more trustworthy one. Universities and scientific institutes increasingly depended on continuous digital access for experimental control, remote teaching, scholarly publishing and institutional administration. Extended outages could interrupt computation, prevent timely analysis and undermine scientific collaboration even when no research instrument was physically damaged. Engineers consequently had to design systems that tolerated equipment failures, traffic changes and disruptions to particular routes. Redundant connectivity, disciplined configuration management and performance monitoring offered complementary means of reducing operational risks. They also required organisational agreements defining how incidents would be escalated and which parties could make decisions affecting shared services. The importance of resilience became especially evident during the coronavirus pandemic, when demand for remote collaboration and university communication services increased sharply. CESNET reported expanded support for videoconferencing and teaching as part of its infrastructure response in 2020. This episode illustrated the wider social function of scientific networks while also revealing their dependence upon trained operators and stable supporting institutions. Resilience should therefore be assessed as a combination of architecture, organisational preparedness and the capacity to adapt services under pressure.

The expansion of CESNET also created opportunities for original research rather than only the adoption of equipment designed elsewhere. Optical transmission laboratories could investigate ways of transporting demanding scientific signals over fibre while retaining characteristics required for precision measurement. The CzechLight family of technologies illustrates the importance of specialised instrumentation and software-controlled optical transport in this research environment. Such work combines photonics, network engineering, measurement science and the practical challenges of operating a production research network. The research value of these systems depends on identifiable experiments and technical performance, not simply on their inclusion in a national infrastructure catalogue. Optical distribution of highly accurate time and frequency signals, for example, serves scientific users whose instruments require synchronisation more exact than ordinary office networking provides. This area shows how the distinction between a research instrument and the communication system carrying its signals can become increasingly blurred. Transfer of expertise from experimental optical networks into routine operation also demonstrates a productive cycle between innovation and infrastructure maintenance. The CESNET network's gradual support for advanced optical services reflects a research tradition extending beyond conventional packet transport.

A shared research network is useful only when researchers can access the relevant services without unmanageable duplication of administrative procedures. The Czech research environment therefore became involved in identity federation, which allows participating institutions to rely on established methods of authenticating their users. Academic roaming arrangements such as eduroam illustrate the practical value of cooperation because visiting students and scientists can connect across participating institutions with familiar credentials. More demanding infrastructures require corresponding arrangements for groups whose members belong to several countries or universities. A national or European service must identify users reliably without assuming that every person is directly employed by its operator. This need encouraged attention to authentication, authorisation, attribute exchange and the formal separation of institutional identity from permission to use a particular resource. Network access and scientific computing are therefore connected by administrative and technical arrangements that are often invisible to ordinary users. An effective identity service reduces friction, but also requires data minimisation, transparent consent or other appropriate legal bases, and timely removal of obsolete privileges. Successful federation depends upon trust among organisations as much as upon the protocols used to exchange digital assertions. The resulting systems became a significant component of Czech participation in cross-border scientific research.

The Perun authentication and authorisation infrastructure provides a particularly relevant example of locally developed software serving wider research cooperation. Developed jointly by CESNET and Masaryk University, Perun supports the administration of users, groups and their access to distributed scientific services. A project consortium may need to authorise researchers from multiple universities, laboratories and countries while maintaining responsibility for sensitive computing resources. Perun addresses this organisational complexity by providing coordinated identity and access management rather than leaving each service to reproduce a separate user directory. Its design is related to European research-authentication initiatives and can interoperate with academic identity federations through eduGAIN. This connection demonstrates that open technical architectures may support a national service while remaining compatible with international communities. Proper access management is also important for accountability, since a researcher should receive permissions appropriate to a project rather than unnecessary authority over unrelated datasets. The software's institutional significance lies in integrating administrative responsibility with a distributed computing environment that no single organisation owns. The Perun experience nevertheless illustrates how a Czech research infrastructure can contribute software solutions to problems shared across Europe.

The development of MetaCentrum added a computing dimension to the national digital infrastructure long before the later prominence of exceptionally powerful supercomputers. Its distributed resources allowed researchers to submit computing tasks to an environment combining capacities located at several institutions. This model offered an alternative to assuming that every research group should purchase and maintain a self-contained computing cluster. Resource sharing required scheduling policies, accounting, software environments and mechanisms to prevent one user's tasks from unfairly excluding others. These arrangements also created new forms of technical expertise in job management, resource monitoring and user support. Computational grids were particularly valuable for workloads consisting of numerous

independent or loosely coupled tasks whose execution could be distributed geographically. They did not automatically replace tightly integrated supercomputers, because demanding parallel simulations may depend on specialised low-latency interconnections. Instead, different infrastructures developed complementary profiles suited to different kinds of scientific problems. The incorporation of MetaCentrum into the CESNET environment helped connect computation with network operation and a wider system of research services. This experience demonstrates why the evolution of digital research infrastructure should be measured through usable scientific workflows as well as hardware procurement.

The growth of cloud computing introduced another organisational model for shared resources, particularly in research programmes needing flexible software environments. A cloud platform can provide computing instances, containers, storage and supporting services without requiring every project to administer the underlying machines. Such flexibility is attractive for groups whose workloads change rapidly or whose software dependencies differ from those of conventional institutional installations. CERIT Scientific Cloud (CERIT-SC) at Masaryk University developed a role in this environment by providing advanced infrastructure and expertise in deploying complex research services. The centre emphasised experimental and interdisciplinary use of computing facilities, working alongside scientific communities with specialised data-management requirements. Its activities therefore involved more than the provision of generic computing capacity, since scientists often needed help adapting particular workflows to distributed platforms. Container orchestration and cloud-native services became relevant as research applications moved towards reproducible and portable deployment models. Yet these techniques introduced governance questions concerning responsibility for configuration, access control, resource consumption and long-term availability. Its contribution illustrates how a university-based organisation can become a national provider without abandoning an active role in methodological experimentation.

A decisive step towards a coordinated national system occurred when CESNET, CERIT-SC and IT4Innovations were brought together in e-INFRA CZ (the national integrated research e-infrastructure). Their cooperation was prepared through a joint project proposed in 2019, and the resulting research infrastructure began operating in 2020. The partners retained distinctive competences rather than merging into an undifferentiated technical organisation. CESNET contributed national communication, data and distributed services, while CERIT-SC emphasised scientific cloud platforms and research-oriented computing support. IT4Innovations brought advanced supercomputing resources and specialised knowledge of computationally intensive scientific problems. The consortium model was important because complex investigations increasingly required access to several of these services within a coordinated workflow. Researchers could benefit from a shared national framework even when their software ran on machines operated by different participating institutions. Such coordination also introduced questions about joint strategy, eligibility for services, technical interoperability and the division of financial responsibility. Official consortium documents specify access arrangements and governance mechanisms, confirming that integrated infrastructure depends upon institutional agreements as well as technology. The development of e-INFRA CZ therefore represents a shift towards national orchestration rather than the disappearance of its individual research centres.

IT4Innovations at VSB–Technical University of Ostrava contributed a specialised computational capability to this wider structure. The centre began operating major supercomputing systems in 2013 and subsequently expanded its capacity as scientific demand increased. Its installations included Anselm, Salomon, Barbora and the Karolina system commissioned in 2021, reflecting successive stages of computational modernisation. Karolina combined conventional processing resources with accelerated components designed for numerical simulations, demanding data analysis and artificial-intelligence workloads. Its purpose within the national ecosystem differed from that of the academic network, because high-performance computation concentrates substantial processing capability rather than primarily transporting information. Nevertheless, a supercomputer becomes useful to geographically distributed researchers only through reliable connectivity, access management and software support. Research expertise in scalable numerical methods and performance engineering also matters, since a poorly designed application can waste even a powerful machine's capabilities. Connections with CESNET and CERIT-SC therefore expanded the effective scientific reach of the centre beyond its physical location in Ostrava. The institutional achievement lay in combining a national computing centre with shared European resources and established academic networks.

European high-performance computing initiatives brought an additional level of infrastructure cooperation to the Czech research environment. The European High Performance Computing Joint Undertaking (EuroHPC JU) created mechanisms for coordinated investment in computing capacity and scientific access across participating countries. The Czech Republic's involvement made it possible to relate domestic investment to wider European priorities in computation, artificial intelligence and advanced scientific modelling. Such programmes are especially consequential for medium-sized research systems, which cannot economically reproduce every specialised computing capability within national borders. Access to machines abroad can complement domestic facilities when workload size or architecture makes an external system scientifically preferable. This principle also underlies the significance of participation in European computing projects and collaborations extending beyond a single host organisation. However, international membership does not itself demonstrate original scientific output, because access must be translated into competent modelling, reproducible analysis and publication. Technical training and applications support help researchers use resources efficiently rather than treating computing time as an unrestricted commodity. European competence-centre initiatives, including EuroCC, sought to distribute expertise to academic users and industry as well as expand access to machinery. The resulting model connected research capability, skills and shared infrastructure in a way that extended beyond conventional national supercomputing policy.

The effective use of research infrastructure also depends upon access policies that can be explained and applied consistently. Large facilities must often distinguish between routine services available to eligible institutions and competitively allocated resources intended for demanding research projects. Scientific assessment of requests should consider methodological quality, computational feasibility and the expected use of scarce technical capacity. Allocation procedures must nevertheless avoid creating unnecessary advantages for institutions already possessing extensive administrative experience. Smaller research groups

may require assistance in preparing applications, adapting software or estimating the resources needed for a planned investigation. International projects create additional difficulties when participants need permission to use resources administered under different legal and institutional frameworks. Consistent access policies become especially important where authentication, research-data protection and project-specific restrictions interact. Transparency about eligibility and limitations can build confidence among researchers who do not belong to the infrastructure operators themselves. A mature national system therefore provides not only equipment but intelligible rules through which scientific users can obtain and responsibly employ it.

Scientific information management emerged as an equally important infrastructure responsibility as laboratories produced larger and more heterogeneous datasets. Storage must be distinguished from preservation, because keeping bits on a functioning device does not guarantee that a future researcher can understand or reuse them. Long-term data stewardship requires documentation, persistent identifiers, metadata, provenance records and appropriate decisions about access rights. Reliable repositories must also account for technological obsolescence, software dependencies, legal restrictions and the possibility that some information cannot be shared openly. These demands affect disciplines differently, from experimental physics and genomics to linguistics, archaeology and social research. A common national technical environment can assist those communities through dependable storage and professional support without imposing one inflexible data model on all research. The development of high-capacity storage within CESNET reflects growing recognition that scientific data are assets requiring coordinated treatment. In 2022 the association reported expanded gross storage capacity of approximately 103 petabytes, illustrating the material scale of this responsibility. That figure describes physical provision, not the amount of scientifically curated or publicly accessible information. The broader challenge is therefore to link storage investment with standards and professional practices capable of making research outputs trustworthy over time.

The European Open Science Cloud (EOSC) initiative provided a framework through which national research-data policies could be integrated with a broader European effort. Its guiding concepts include making data findable, accessible, interoperable and reusable (FAIR). These principles do not require all information to be publicly disclosed, because legitimate ethical, legal and security restrictions may limit access. They do require research communities to provide intelligible metadata and procedures that support appropriate discovery and reuse. In the Czech Republic, the EOSC CZ programme brought together infrastructure providers and research institutions to develop shared approaches to data management. Its national work involves coordination, training, metadata systems and the gradual construction of interoperable repository services. The EOSC-CZ project identifies the e-INFRA CZ partners among the organisations supporting the implementation of the national research-data environment. This relationship demonstrates a shift from managing individual institutional files towards planning the lifecycle of research information at national and European levels. The historical significance lies in the emergence of a coordinated architecture and professional community for long-term research-data management.

A particularly concrete development was the National Repository Platform for Research Data, whose implementation period began in January 2024 and continues beyond 2025. Led by CESNET, the project was designed to provide shared repository infrastructure, support data management and connect diverse research communities with common technical services. Its stated tasks include repository deployment, metadata management, licensing, access control, training and cybersecurity support. These are not merely administrative additions, because poorly described or insecure data may be unusable even when substantial investments have been made in computation. Repository development also requires cooperation between research libraries, information specialists, developers and disciplinary scientists who understand the meaning of particular datasets. The platform's architecture envisages several software environments rather than one mandatory format for every participating discipline. Its support for professional data stewards recognises that reliable information management requires trained people capable of linking policy with daily research practice. The project documentation specifies an implementation horizon ending in 2028, so its planned outcomes must not be described as fully delivered by the historical endpoint of this study. By 2025 the initiative represented a major institutional commitment to remedying fragmented practices in the storage and reuse of scientific information. Its future success would depend upon interoperability, sustained funding and the willingness of scientific communities to adopt well-supported data-management procedures.

The relationship between general-purpose digital infrastructure and discipline-specific research services illustrates the diversity of scientific requirements. Biological researchers may need databases and analysis platforms that follow international community standards, while linguistic researchers require corpora, annotation formats and persistent access to textual resources. Czech participation in ELIXIR, the European research infrastructure for life-science data, provides one example of such specialised coordination. The Czech node of the European life-science data infrastructure (ELIXIR CZ) brings together several organisations and supports databases, software tools, interoperability and training across biological research communities. Its scientific activities cannot be reduced to hosting computers, since the interpretation and integration of biological information depend upon disciplinary expertise. The participation of CESNET and Masaryk University connects specialised bioinformatics requirements with broader networking and computational capacity. Other research fields similarly benefit when specialist centres can rely on common identity services and durable repositories without surrendering control of their scientific methods. This pattern favours shared technical foundations combined with community-specific governance and metadata standards. The case demonstrates that integration does not necessarily require centralisation of every database or research activity.

The national research network operated within a broader Internet ecosystem involving domain management, traffic exchange and private communications providers. CZ.NIC became the administrator of the Czech national Internet domain and developed specialised expertise in domain-name infrastructure, security and technical services. Such organisations affect scientific activity because dependable naming and routing are necessary conditions for access to online research resources. NIX.CZ (Neutral Internet Exchange in the Czech Republic) provided a further form of national Internet cooperation by enabling participating networks to exchange traffic

directly within a coordinated environment. The resulting infrastructure relationships were not identical to those of CESNET, because commercial networks and domain registries serve broader constituencies than universities alone. Nevertheless, coordination among these organisations could improve operational knowledge and incident response across the national digital environment. Technical initiatives involving secure domain services and protective arrangements also helped establish a local professional community concerned with the reliability of network operation. The distinction between a national Internet exchange and a research network should remain clear even when the same engineers or organisations participate in joint activities. Scientific independence depends partly upon such wider Internet capabilities, but those capabilities cannot be claimed exclusively as achievements of academic research. Their evolution demonstrates how Czech digital infrastructure became an ecosystem of interdependent public, academic and private actors.

Cybersecurity coordination became indispensable as research networks increasingly carried valuable information and provided access to expensive facilities. CESNET developed specialised incident-response capabilities for its own constituency and contributed to wider discussion of national security practices. The national Computer Security Incident Response Team (CSIRT.CZ) evolved through work undertaken within CESNET before its operation was transferred to the CZ.NIC association in 2011. A memorandum signed in December 2010 established the framework for this new national role, while later agreements clarified responsibilities and relationships with public authorities. National and academic incident-response functions remained distinct, even though both depended upon technical expertise and cooperation with network operators. Their effectiveness required exchanging reliable information about incidents while respecting confidentiality and the legitimate interests of affected organisations. International professional communities also mattered because malicious activity frequently crossed national boundaries and did not conform to the jurisdiction of any one response team. The history of CSIRT.CZ shows how experimental and research-community expertise could contribute to a continuing national operational service. Instead, it illustrates a layered approach in which local operators, sectoral teams and national coordination structures assume complementary responsibilities.

The establishment of the National Cyber and Information Security Agency (NÚKIB) introduced a clearer institutional centre for national cybersecurity governance. The agency began operating on 1 August 2017 under the legislative framework amending the Czech Cyber Security Act. Its responsibilities include cybersecurity administration and areas of information and cryptographic protection defined by law. This role differs from operating a research network, because the agency exercises public authority and coordinates national security measures. Universities and research infrastructures nevertheless belong to the wider environment affected by cybersecurity regulation, risk assessment and information sharing. Security governance becomes complex when organisations simultaneously operate scientific services, process personal data and cooperate with international partners. It requires procedures capable of assigning responsibility without preventing legitimate research or treating every academic system as having the same risk profile. The agency's official institutional history confirms the August 2017 starting date and its central administrative responsibilities. The historical significance of this development lies in the

growing recognition that digital resilience is a matter of public institutions and enforceable responsibilities, not solely technical good practice. It also reinforced the need for research organisations to combine specialist innovation with systematic operational security.

European cybersecurity policy added a further layer of obligations and coordination to this national setting. Directive (EU) 2022/2555, commonly known as the NIS2 Directive, sought to establish stronger and more consistent cybersecurity risk management across member states. Its scope encompassed several categories of essential and important organisations, reflecting the economic and social dependence on reliable digital services. The Czech response involved legislative and organisational adaptation during the first half of the 2020s rather than instantaneous implementation at the directive's adoption. A new Czech cybersecurity law was signed by the president in June 2025, with the legislative process anticipating entry into force later that year. These dates are historically important because a law's announcement, publication and operational effect are distinct stages that should not be conflated. Research infrastructures faced the broader challenge of understanding which duties applied to particular services and how regulation interacted with their scientific mission. Compliance could provide useful clarity about risk management, but it also required resources, staff training and organisational changes. Cybersecurity governance by 2025 had thus become inseparable from the sustainability of shared digital research infrastructure.

The cooperation between infrastructure providers and technological enterprises created opportunities for innovation extending beyond academic laboratories. High-performance computing can assist companies in engineering simulation, materials analysis and the testing of data-driven products, but such cooperation demands reliable access and confidentiality. Networking specialists may work with equipment suppliers to develop optical systems, monitoring tools or more efficient methods of transporting scientific signals. University groups can contribute algorithmic expertise, while infrastructure operators provide demanding environments in which methods are evaluated under realistic conditions. Publicly supported centres therefore sometimes act as intermediaries between fundamental research and practical industrial development. The significance of these activities should be assessed through demonstrable technical outcomes, independent evaluations and clearly documented partnerships rather than publicity claims alone. The relationship can also create tensions when private users seek priority access to facilities whose principal purpose is scientific research. Transparent resource allocation and appropriate pricing or contractual conditions are needed to preserve public accountability. Programmes aimed at assisting industrial users with advanced computing recognise that expertise and training can be as important as access to machines. The Czech experience suggests that productive partnerships emerge when research missions, public responsibilities and commercial expectations are kept analytically distinct.

Specialised digital infrastructures cannot become effective without a professional workforce able to translate researchers' problems into reproducible technical workflows. Network engineers, systems administrators, cybersecurity analysts, data stewards and software specialists perform different but mutually dependent functions. The complexity of modern research services also creates demand for staff who can communicate with scientists lacking deep experience in infrastructure management. Universities contribute education and doctoral

training, while national research centres provide workshops, documentation and expert consultation. Cross-border projects add opportunities for learning operational practices used by other European research infrastructures. The EuroCC competence-centre approach illustrates an effort to address disparities in advanced computing skills while connecting academic and industrial communities. Similarly, EOSC-related initiatives developed training activities focused on data management, repository services and the FAIR principles. The role of specialised support workers deserves recognition even when their achievements are not normally represented by journal publications. By 2025, the human infrastructure surrounding digital systems had become a central condition of Czech scientific competitiveness.

Long-term sustainability remains one of the most difficult questions facing the national digital research ecosystem. The construction of a new computing cluster or optical link is generally more visible than the continuous expenditure needed to operate and renew it. Yet electricity, cooling, software maintenance, physical security, network leases, equipment replacement and specialist salaries impose substantial recurrent costs. Infrastructure investment also creates long-term expectations among users who may build research methods around the availability of particular resources. Dependence upon fixed-term European projects can create problems if operating commitments extend beyond the period covered by initial grants. A responsible strategy must therefore distinguish capital financing from predictable support for essential continuing services. Environmental impacts have become increasingly important as advanced computing systems demand substantial energy and careful management of equipment lifecycles. Efficiency improvements should be assessed against real scientific workloads, since a high nominal performance figure does not guarantee economical use of energy. Sustainable development also requires deciding which services should be maintained nationally and which are better accessed through reciprocal European cooperation. The Czech infrastructure model offers possibilities for shared planning, but it cannot eliminate the financial trade-offs inherent in modern scientific computation.

The question of digital sovereignty requires particular care because self-sufficiency is not a realistic description of contemporary research computing. Czech infrastructure depends upon internationally manufactured processors, networking equipment, specialised software and technical standards developed by multinational communities. Conversely, Czech organisations contribute to European research services and can influence their design through sustained professional participation. Sovereignty in this context is better understood as the capacity to make informed choices, retain critical expertise and avoid unnecessary dependence on a single provider. Open interfaces, portable research software and documented data formats can reduce the risk that a project becomes trapped within one technological platform. At the same time, shared European infrastructure may provide greater resilience and scientific opportunity than attempting to reproduce every facility within national borders. Cybersecurity and intellectual-property responsibilities complicate these choices where the location of data processing or storage has legal implications. An economically sensible system must balance independent national capability with reciprocal access, operational trust and collaboration. Between 1993 and 2025 the Czech experience increasingly reflected this nuanced balance between domestic competence and European integration.

Assessing the achievements of national digital infrastructure requires evidence beyond the number of installed machines or the total length of fibre-optic cable. Useful indicators include service reliability, scientifically justified access, the diversity of research communities served and demonstrable contributions to publications or experiments. Original technological research should be identified separately through publications, documented prototypes, technical validation or internationally adopted methods. A national computer centre may have exceptional operational value even when many of the research results obtained through its machines were produced by external scientific teams. Conversely, an innovative networking instrument may represent an original contribution despite being deployed at a relatively modest scale. Measures of impact also need to account for user training, accessibility for regional institutions and collaboration with smaller research groups. International partnerships offer valuable evidence of integration, but participation alone does not establish leadership in every related technological field. Policy evaluation should distinguish capacity that has been announced, capacity actually commissioned and resources routinely available under published access conditions. These distinctions are essential when examining programmes that remained under development at the endpoint of 2025. A historically sound assessment therefore treats technological scale, scientific originality and organisational effectiveness as interconnected but non-identical dimensions.

By the end of 2025, Czech digital research infrastructure had developed into a multi-layered system combining national institutions with European frameworks. CESNET connected research organisations and provided services extending from communications to security and data management. CERIT-SC contributed flexible scientific computing and practical expertise in cloud-oriented research environments, while IT4Innovations supplied specialised high-performance computational resources. Their cooperation through e-INFRA CZ supported a more coherent national approach to the movement, processing and preservation of scientific information. European partnerships involving GÉANT, grid and computing infrastructures, and open-science programmes enlarged the possibilities available to domestic research communities. The emergence of national cybersecurity authorities and specialised response teams also demonstrated that trust and resilience had become institutional concerns of scientific and public policy. Important challenges persisted in sustaining expensive facilities, preparing specialist staff, allocating scarce resources fairly and protecting research information without obstructing collaboration. The history of this period therefore offers neither a simple success narrative nor a model in which technological progress follows automatically from European investment. The Czech experience illustrates how shared digital resources can become a foundation for research independence precisely through carefully managed cooperation beyond national and institutional boundaries.

Conclusion

Czech Computer Science and Information Technology, 1993–2025: From Post-Socialist Transformation to an Internationally Integrated Digital Innovation Ecosystem

The development of Czech computer science and information technology between 1993 and 2025 reveals a transformation that cannot be reduced to the diffusion of computers or the commercial success of software companies. Its historical significance lies in the convergence of inherited scientific capabilities, political openness, institutional reform, technical experimentation and market initiative. The independent republic did not invent a national tradition of computation, but acquired responsibility for sustaining and renewing an already established one. Over the following decades, universities, research institutes, entrepreneurs and public authorities responded to technological changes whose consequences repeatedly exceeded initial expectations. Their activities produced a varied landscape in which abstract algorithms coexist with industrial software, public digital services and internationally distributed research infrastructures. This variety explains why the country's digital development must be assessed through intellectual, technological, economic and social evidence rather than through a single ranking. The successes of one sector do not automatically imply equivalent achievement in another, while national performance cannot be inferred from the reputation of a few prominent companies. Equally, limitations in public administration or enterprise digitalisation do not negate original contributions made in theoretical computer science and computational research. Taken together, the findings of this volume establish a history of cumulative adaptation, selective excellence and unresolved structural tensions.

The first conclusion concerns the relationship between the political changes of 1989 and the institutional watershed of 1993. The end of state socialism removed restrictions on academic exchange, private enterprise and access to foreign technologies before the new republic formally came into existence. Independence subsequently reorganised the legal and administrative conditions under which inherited research institutions and technical communities operated. These transitions were complementary, but they should not be collapsed into a single event or described as the spontaneous creation of Czech computing. Earlier work in mathematical logic, cybernetics, automatic control, programming and experimental computer construction remained part of the country’s intellectual resources. The legacy of the Czechoslovak computing pioneers was valuable not because their machines could compete indefinitely with rapidly changing commercial hardware, but because they had established engineering experience and research ambitions. Technical universities and academic institutes preserved expertise that younger specialists could adapt to emerging international methods. At the same time, the transition exposed weaknesses associated with restricted technological exchange, uneven equipment and inherited organisational dependencies. The historical achievement after 1993 therefore consisted in transforming institutional possibilities without extinguishing the knowledge on which further innovation depended. Such continuity is an essential corrective to

accounts that portray post-socialist technological development solely as the importation of Western products.

A second finding concerns the gradual replacement of a relatively centralised computing environment by a more heterogeneous combination of private markets, public research and international partnerships. During the 1990s, personal computers, local networks and commercial software altered the practical meaning of informatics for schools, enterprises and households. New firms learned to develop products for customers whose expectations were no longer defined primarily by administrative planning. Market competition created incentives for usability, maintenance, distribution and rapid technical improvement, although it also exposed enterprises to financial uncertainty. The emerging Internet amplified these changes by allowing services and information to reach users beyond established institutional channels. Czech businesses consequently acquired opportunities to specialise in locally relevant services before confronting international competition in selected segments. This entrepreneurial opening did not replace universities or public institutes as sources of advanced knowledge. Rather, it created new routes through which engineering competence could enter commercial products, private employment and international technology networks. The decisive historical change was therefore the diversification of organisations capable of creating and applying digital knowledge.

The development of Internet infrastructure provides a particularly clear illustration of this interdependence between scientific continuity and economic transformation. Academic networking preceded the mass commercial Internet and supplied technical knowledge essential to its subsequent expansion. The national CESNET (Czech Education and Scientific Network) infrastructure, launched in 1993, contributed to the establishment of a national environment for research communication and technological experimentation. Commercial connectivity developed through different incentives, especially the demand for affordable public access, information services and business communication. The expansion of domestic exchanges, domain administration and broadband access gradually reduced dependence upon isolated technical arrangements. Yet the benefits of connectivity depended on more than transmission capacity because useful digital networks also require institutions, skills and dependable services. Academic infrastructures later supported high-speed data exchange, identity management, security monitoring and access to distributed computing resources. The institutional significance of these developments becomes clearer when academic and commercial networks are considered together. The resulting division of labour between public research networks and commercial telecommunications was sometimes permeable but never insignificant. Czech experience demonstrates that a viable Internet ecosystem is the outcome of coordinated technical, organisational and economic development, rather than a single founding event or technological purchase.

Membership of the European Union from 2004 changed the scale and context within which these activities could develop; research cooperation, academic mobility and access to European programmes enabled Czech institutions to participate in projects larger than their domestic resources could ordinarily sustain. European integration also encouraged common standards of project evaluation, technological interoperability, financial management and collaborative research. For computer science, the consequences were visible in infrastructure investment and

in the normalisation of cross-border research teams. Commercial firms gained opportunities to recruit internationally, sell services throughout the internal market and participate in transnational supply chains. These opportunities nevertheless operated unevenly because successful participation required prior organisational capacity and specialist expertise. Institutions already possessing competent researchers and credible international networks could often exploit new programmes more effectively than smaller organisations. European support should consequently be treated as an enabling condition rather than as an automatic cause of intellectual originality or commercial success. The strongest outcomes emerged where external opportunities reinforced durable national capabilities and clear research priorities. This interaction between domestic foundations and European frameworks became a defining characteristic of the Czech digital ecosystem.

Theoretical computer science illustrates the continued importance of knowledge whose value cannot be expressed through immediate market revenue. Czech mathematicians and computer scientists contributed to graph theory, computational complexity, mathematical logic, algorithmic structures and the formal analysis of computation. Research associated with Jaroslav Nešetřil, Pavel Pudlák, Jan Krajíček and other scholars demonstrates the international relevance of specialised intellectual schools. Their achievements should be assessed through the questions they formulated, the results they proved and the methods other researchers subsequently developed from them. Formal results often influence software engineering indirectly by clarifying what can be computed, verified or approximated within specified resource limits. Such contributions are easily obscured when technological innovation is defined exclusively in terms of patents, devices or commercial products. The national significance of a research school also depends on doctoral training, seminars and the capacity to sustain rigorous discussion across generations. International co-authorship does not diminish these achievements, provided the intellectual contribution and institutional context are described accurately. An account of Czech technological modernisation would therefore remain incomplete without sustained attention to its abstract scientific foundations. The case confirms that fundamental inquiry and industrial usefulness are related, but neither is a satisfactory substitute for the other.

Related advances in formal verification and software engineering reveal how mathematical rigour can be connected to practical reliability. Czech research groups developed approaches to component-based software, model checking, static analysis and the automated examination of programme behaviour. Work associated with SOFA, DIVINE, Predator and Symbiotic illustrates distinct attempts to detect defects or reason about complex systems before failures occur in practice. The importance of these projects lies in their methods and reproducible research results rather than in the number of commercial products bearing their names. Formal verification cannot establish absolute safety when models omit relevant assumptions or when the operating environment differs from the one analysed. Nevertheless, it provides techniques for expressing properties precisely and assessing system behaviour more systematically than informal testing alone. This tradition also supports the development of secure industrial controllers, dependable infrastructure and better understood automated systems. Open research software has facilitated international criticism, comparison and adaptation of methods

originally pursued in Czech institutions. The broader conclusion is that reliability is an intellectual and organisational achievement, not a quality conferred automatically by the use of modern programming tools.

Artificial intelligence added a different form of dynamism to the research system, although its development was not a sudden consequence of the recent popularity of generative models. Czech investigators worked on knowledge representation, planning, multi-agent coordination, statistical learning and intelligent decision-making before deep neural networks dominated public attention. Research undertaken in Prague and Brno connected formal reasoning with applications in language, robotics, security and complex information environments. International careers, including those of researchers educated within Czech institutions, broadened the influence of these traditions while complicating simple national attributions. The later adoption of deep learning expanded the scale of problems addressed through speech analysis, computer vision and data-intensive prediction. Generative systems subsequently intensified questions of model reliability, computational expense, linguistic coverage and human oversight. Scientific progress in these areas must be distinguished from the incorporation of externally developed models into commercial services. A Czech enterprise may implement advanced artificial intelligence successfully without having originated the learning method it employs. Conversely, a theoretical contribution developed through international collaboration can be scientifically significant without producing an immediately recognisable consumer product. These distinctions are necessary if the country's contribution to artificial intelligence is to be described without exaggeration or undue modesty.

Computational linguistics shows how a national scientific tradition can contribute internationally through the demands of a particular language; research on Czech morphology, syntax and semantic structure required methods capable of representing grammatical complexity and linguistic variation. The Prague Dependency Treebank, Czech National Corpus and related linguistic resources supplied structured material for the systematic investigation of language. Tools such as MorphoDiTa and UDPipe connected these resources with reproducible procedures for automated language processing. The resulting infrastructure has supported linguistic scholarship as well as multilingual research, digital humanities and practical language technologies. This achievement cannot be understood exclusively as an application of imported computational methods because the construction of high-quality annotated resources requires distinctive linguistic expertise. At the same time, technological advances depended upon collaboration between philologists, programmers, statisticians and international partners. The expansion of neural language models introduced new capabilities without eliminating the importance of transparent annotation and carefully evaluated datasets. Czech computational linguistics thus represents an especially clear example of continuity between disciplinary inheritance and methodological innovation. Its wider lesson is that local knowledge can acquire global scientific relevance when transformed into reliable and shareable research resources.

Cybersecurity provides one of the clearest examples of a field in which fundamental research, professional infrastructure and commercial activity became mutually reinforcing. Czech teams investigated cryptographic implementations, network monitoring, malicious software and the conditions under which supposedly secure systems fail. Research identifying weaknesses in real

cryptographic products demonstrated that security must be evaluated against practical implementations rather than mathematical designs alone. University groups, academic networks and national incident-response teams consequently contributed different but complementary forms of expertise. Commercial antivirus enterprises developed another route towards technological impact by confronting evolving threats across large populations of users. The sector's public visibility should not obscure the distinction between discovering a vulnerability, developing a defensive method and operating a product at commercial scale. It also illustrates how commercial success creates responsibilities concerning data collection, transparency and the handling of incidents. National cybersecurity governance gradually acquired specialised institutional forms, but resilience remained distributed across public authorities, service providers, researchers and users. Trustworthy information systems therefore depend on continuous technical scrutiny combined with accountable organisational practices. Their development is best understood as an enduring process of adaptation rather than a condition permanently achieved through legislation or software procurement.

The growth of high-performance computing changed the material possibilities of scientific investigation across many disciplines; Czech computing research moved from departmental resources towards increasingly capable national infrastructures, particularly through IT4Innovations in Ostrava. Systems including Anselm, Salomon, Barbora and Karolina represented successive stages in the expansion of computational capacity rather than interchangeable symbols of technological progress. Their scientific value depended on the quality of numerical methods, software environments, user support and research problems addressed. Parallel algorithms, optimisation procedures and scalable solvers were essential in translating expensive hardware into credible results. Czech contributions to tools such as ESPRESO and PERMON show why expertise in algorithms and computational mechanics matters alongside hardware acquisition. Access to shared facilities also allowed researchers in chemistry, engineering, medicine and other sciences to undertake calculations beyond the reach of ordinary institutional resources. Large infrastructures nevertheless generate operating costs, technical dependencies and obligations extending well beyond their construction phase. Consequently, the assessment of supercomputing investment must include sustained scientific use, training and international accessibility rather than processor performance alone. The Czech experience illustrates how infrastructure becomes productive when scientific communities can both use and improve it.

Computer vision, graphics and robotics further demonstrate the advantages of interaction between mathematical research and engineering experimentation. Work on visual features, geometric reconstruction and the interpretation of images contributed methods important to international computer vision. Research in graphics and rendering addressed the realistic simulation and visual communication of complex environments. Czech laboratories also advanced techniques for medical image analysis, robot navigation, autonomous aerial systems and industrial manipulation. These fields are connected, yet their standards of validation remain different because a reliable geometric estimate does not automatically guarantee safe physical behaviour. Experimental robots must operate under uncertainty concerning sensors, moving objects, mechanical constraints and human intentions. Likewise, systems intended for medicine

or industrial inspection require evaluation against the particular risks of their application. Collaboration among universities, research institutes and firms expanded opportunities to move promising methods into operational settings. Nevertheless, the difference between a laboratory demonstration and a dependable commercial deployment remains central to any rigorous assessment. Czech achievements are strongest when methodological originality is accompanied by reproducible evaluation and technically credible implementation.

The emergence of quantum computing and renewed semiconductor ambitions towards 2025 introduced another strategic dimension to the national research landscape; Czech quantum research drew upon traditions in optics, information theory and experimental physics that long preceded national plans for new computing facilities. Work in Prague and Olomouc contributed to internationally connected investigations of quantum states, communication and computation. The inauguration of the VLQ quantum computer at IT4Innovations in September 2025 marked an infrastructural milestone within a European programme rather than proof that all prospective applications had already been realised. Semiconductor research and specialised processor design similarly linked university expertise with international industrial supply chains and investment. Strategic initiatives adopted in 2024 and 2025 sought to strengthen the national role in these technologies while recognising the scale of European competition. Their significance cannot be assessed simply by treating every announcement as an operational facility or every proposed investment as completed production. Questions of workforce availability, technology transfer, energy use and long-term financing remained decisive. These developments consequently represent promising capacities and emerging choices as much as settled achievements. Their inclusion in the historical account clarifies how the priorities of 2025 extended beyond conventional software markets into hardware, scientific instruments and strategic digital sovereignty.

Institutionally, the Czech research system remained polycentric, although its resources and international visibility were unevenly distributed. Prague retained a substantial concentration of universities, specialised laboratories, public authorities and research-intensive enterprises. Charles University sustained internationally connected work in theoretical computer science, computational linguistics and software research. The Czech Technical University in Prague combined computer vision, artificial intelligence, robotics and engineering-oriented systems development. Brno constituted a second major centre through Masaryk University, Brno University of Technology and an exceptionally active community of technology enterprises. Ostrava acquired a distinctive position through large-scale computing and the research capacities associated with IT4Innovations. The Academy of Sciences added continuity in information theory, mathematical methods, control and computational research beyond conventional university structures. Smaller regional centres contributed specialised expertise in speech technology, fuzzy systems, image analysis, mechatronics and applied informatics. This distribution should be evaluated through complementary research profiles rather than through an assumption that all cities must reproduce the same disciplines. A resilient national system requires strong major centres and credible pathways for cooperation with smaller institutions.

The scientific schools of Prague provide a particularly revealing example of how continuity is maintained through intellectual communities rather than institutional names alone; traditions in

discrete mathematics and formal reasoning helped sustain inquiry that did not depend directly upon short commercial cycles. At the same time, specialised groups in machine perception, intelligent systems and software architecture developed research agendas responding to changing technological possibilities. Doctoral education and international seminars linked established investigators with younger researchers pursuing different questions. Shared academic settings facilitated exchanges between mathematicians, linguists, programmers and robotics specialists. Yet such exchange was productive only where disciplinary standards remained sufficiently clear for contributions to be assessed critically. Prague's institutional concentration also supported cooperation with industry and international research partners, although these relationships varied in intensity and purpose. The lesson is not that proximity alone creates innovation, but that continuity and diversity can lower the barriers to ambitious interdisciplinary work. The achievements associated with Prague therefore reflect networks of people, methods and institutions rather than the prestige of a single university. Their future significance depends on allowing younger scholars to reformulate inherited problems instead of merely reproducing established reputations.

Brno's development demonstrates a related but distinct institutional pathway, shaped by research specialisation and entrepreneurial connectivity. Masaryk University's Faculty of Informatics, established in 1994, became an important environment for advanced computer science and specialist education. Brno University of Technology's Faculty of Information Technology, formed in 2002, further strengthened the city's research and professional infrastructure. Their work encompassed formal verification, information security, speech technology, data systems and other computational disciplines. Research achievements could interact with commercial demand through graduates, collaborative laboratories and specialist enterprise networks. The regional innovation centre JIC contributed to the wider institutional environment supporting entrepreneurial experimentation and business development. International companies established engineering activities in the city, creating employment while introducing new organisational practices and competition for qualified specialists. Such investment did not automatically convert foreign intellectual property into Czech-owned innovation, but it could strengthen local technical expertise and professional networks. The combination of strong educational institutions and an internationally connected labour market was particularly important to Brno’s digital development. Its experience underlines the need to assess technological ecosystems through accumulated capabilities rather than through company counts alone.

Ostrava illustrates a third route by which a regional research centre can acquire international significance through focused infrastructure and specialised methodology; the development of IT4Innovations required cooperation between scientific leadership, university administration, national policy and European programmes. Large computing installations gave the city visibility within research networks extending far beyond the Moravian-Silesian region. Yet the deeper intellectual achievement lay in the development and maintenance of algorithms, numerical software and expert teams able to exploit that capacity. Applied modelling, emergency-response tools and projects supporting scientific workflows connected computing with practical needs. Participation in European supercomputing initiatives further placed Ostrava within the

governance of shared international resources. The introduction of quantum infrastructure by 2025 extended the city's technological horizon without replacing established high-performance computing research. These developments also created expectations concerning local education, industrial cooperation and the retention of technical expertise. The benefits will remain dependent on sustained access, credible research priorities and the renewal of scientific personnel. Ostrava therefore demonstrates how regional differentiation can increase national technological capacity when specialisation is connected to wider cooperative systems.

The Academy of Sciences and regional universities preserve another dimension of scientific continuity that cannot be measured through high-profile facilities alone. The Institute of Computer Science and the Institute of Information Theory and Automation maintain research environments concerned with computation, modelling, inference and control. Their programmes illustrate why fundamental scientific institutions remain relevant even as commercial software markets transform rapidly. Regional universities in Plzeň, Olomouc, Liberec, České Budějovice and Zlín add research specialisations shaped by local expertise and educational missions. Contributions in probabilistic methods, image processing, speech recognition, intelligent control and applied information systems diversify the national intellectual landscape. Such groups often participate in international communities without commanding the same institutional visibility as larger metropolitan centres. The sustainability of their work depends upon stable doctoral pathways, access to shared infrastructures and opportunities for collaboration. Excellence should accordingly be identified through published results and sustained research activity rather than assumed from organisational size. Effective cooperation allows a relatively small national scientific system to avoid unnecessary duplication and make specialised capabilities more widely available. The persistence of these communities is a central part of the Czech record of innovation after 1993.

Research networking and shared digital infrastructure constitute one of the most durable institutional achievements of the period; the creation and subsequent development of CESNET provided a national foundation for research communication and advanced networking services. Complementary capabilities emerged through distributed computing, scientific cloud resources and high-capacity repositories. The cooperation between CESNET, CERIT-SC and IT4Innovations within e-INFRA CZ expresses a deliberate movement towards an integrated research infrastructure. This arrangement allows investigators to combine data transport, processing, storage and specialist support rather than treat these functions as unrelated services. International links with European networking and computing programmes further enlarge the scientific resources available to Czech research institutions. At the same time, integration creates demanding obligations concerning cybersecurity, interoperability, cost allocation and technical governance. A shared infrastructure is successful only when its services are accessible to researchers with different levels of computational expertise. Its public value also depends on transparent priorities and the long-term preservation of research data and skills. Czech digital infrastructure thus demonstrates the importance of organisational innovation alongside technological investment.

The economic history of the period reveals how the country moved from a relatively small domestic software market towards a diverse and internationally connected digital industry. The

first private enterprises built businesses around office software, information systems, specialised utilities and professional services. Subsequent generations increasingly addressed global customers through digital platforms, subscriptions, cloud-based products and exportable technical expertise. Seznam.cz illustrates the continued commercial potential of services adapted to national linguistic and market conditions. Companies such as GoodData, Ataccama, Y Soft, Productboard and other internationally oriented businesses demonstrate different routes towards external markets. Their trajectories should not be compressed into a single model because funding, customer relationships, research intensity and ownership structures differ substantially. Some firms developed proprietary products, while others combined implementation services with long-term engineering partnerships. Foreign investment could accelerate expansion but could also alter strategic control, employment structures and the location of commercial returns. Accordingly, national industrial success should be examined through the location of development, ownership of knowledge, professional skills and durable value creation. The presence of internationally visible companies is an important achievement, but it is not a complete measure of innovation capacity.

The Czech antivirus industry provides the strongest illustration of how a relatively specialised field can generate globally recognised software enterprises; the independent development of Avast and AVG drew upon technical skills, changing personal computing markets and sustained exposure to practical security problems. Their products required continuous analysis of evolving threats and increasingly sophisticated ways of distributing updates to large user communities. International expansion enlarged commercial opportunities while also creating complex governance and reputational risks. Corporate transactions, including the acquisition of AVG by Avast and the later formation of Gen Digital, demonstrate that successful enterprises may undergo major changes in ownership and organisational identity. Such transformations should not be confused with the disappearance of the technical expertise through which earlier products were developed. They also show why ethical responsibility matters to the evaluation of a digital industry whose services depend on users' trust. Security incidents and disputes concerning data practices reveal weaknesses that commercial indicators alone cannot capture. The sector's significance therefore extends beyond export revenue to questions of technological reliability, privacy and institutional accountability. In this respect, Czech cybersecurity offers both an example of industrial competitiveness and a reminder of the obligations accompanying it.

Game development and creative computing form a different but equally important expression of Czech technological entrepreneurship. Studios including Bohemia Interactive, SCS Software, Amanita Design and Warhorse Studios developed products for international audiences with distinct technological and artistic ambitions. Their work combined programming, simulation, visual design, narrative, sound and extensive testing in commercial production environments. Simulation-focused studios required attention to performance, modelling and complex interactions within large digital worlds. Other developers established reputations through visual originality, carefully designed interaction and distinctive cultural expression. Industry reports show that international markets became central to the economic viability of Czech game production. Yet employment numbers or sales totals cannot alone reveal the technical originality or cultural significance of individual projects. Creative computing also exposes vulnerabilities

associated with long development cycles, intellectual property management and dependence on distribution platforms. Education and collaboration across engineering and artistic disciplines became especially important in sustaining the sector's professional skills. Its trajectory demonstrates that innovation can arise through the integration of technological competence with cultural creativity rather than through conventional scientific research alone.

The digital transformation of established Czech manufacturing shows how information technology can modernise sectors whose foundations long predate the Internet economy; automotive production, machinery, industrial equipment and electronics increasingly integrated computational modelling, automated control and data-driven coordination. Digital twins and advanced manufacturing systems could improve diagnosis, traceability and process planning when integrated with suitable organisational practices. Projects involving industrial firms and research organisations reveal the importance of joint experimentation rather than unilateral technology procurement. The country's semiconductor activities add a hardware dimension through manufacturing, research infrastructure and specialised engineering competence. Nevertheless, a new factory announcement, research strategy or demonstration platform is not equivalent to fully realised technological independence. International supply chains remain essential to advanced manufacturing, while investment requirements often exceed the resources of individual domestic actors. Adoption of industrial software can also be uneven because small enterprises face financial and staffing constraints unlike those of major manufacturers. The value of digitalisation must consequently be assessed through measurable improvements in production, reliability and organisational capacity rather than the presence of fashionable technological terminology. Czech industrial experience demonstrates the possibility of renewing established economic strengths without assuming that every enterprise can modernise at the same pace.

Public administration provides an equally important test of whether digital technologies produce benefits beyond scientific institutions and competitive firms. The expansion of Czech POINT, electronic data boxes, state registers, the Citizen Portal and electronic identity services altered the channels through which people interact with public authorities. Digital systems promised faster exchange of information, reduced duplication and easier access to selected services. Their effectiveness nevertheless depended on clear legal responsibilities, reliable identifiers and interoperability between institutions. Inconsistent data structures or fragmented procurement could reduce the practical benefits of otherwise well designed electronic interfaces. The creation of specialised coordination bodies strengthened the institutional recognition of digital government as a long-term public task. Electronic health, education and financial services further demonstrated that digital transformation concerns organisational arrangements as well as technology. The availability of a service cannot be equated with its successful use by every member of the population. A mature assessment must consider accessibility, security, comprehensibility and the ability to obtain help when automated processes fail. Progress in electronic government is therefore meaningful when technical development is accompanied by demonstrable improvements in administrative quality and public trust.

The social consequences of digital development reveal both progress and inequalities that aggregate economic indicators may obscure; wider Internet access changed education,

communication, employment, consumer services and participation in public life. Universities and professional training programmes expanded opportunities to acquire computational knowledge, while industry demand encouraged new specialised career paths. Yet unequal confidence with digital tools continued to affect older users, people with disabilities and individuals with limited financial or educational resources. Geographic differences in connectivity and institutional support could intensify these problems even where national coverage indicators improved. The European Commission's 2025 assessment recognised progress in digital skills while identifying continuing limitations in high-capacity connectivity and business transformation. Such findings indicate that technological availability and social capability should be evaluated separately. Digital inclusion requires accessible services, appropriate teaching, clear information and the preservation of practical alternatives where they remain necessary. Human capabilities therefore constitute infrastructure in a broader sense because digital systems cannot fulfil their social purpose without competent and confident users. The long-term success of Czech digital modernisation depends on reducing these barriers rather than celebrating technology adoption in isolation.

The national research and innovation system nevertheless faces limitations that cannot be resolved through historical reputation or isolated technological successes. Access to venture finance, managerial experience and large international markets influences whether promising companies can grow without losing their development base. Public research organisations must reconcile stable scientific programmes with demanding competitive funding cycles and administrative responsibilities. Advanced computing, semiconductor development and artificial intelligence require specialised personnel whose skills are sought internationally. Competition for talent can strengthen professional mobility but also create vulnerabilities for smaller institutions and enterprises. The uneven geographical concentration of research capacity makes regional cooperation essential rather than merely desirable. Public digital systems face persistent questions of interoperability, procurement capability and the secure management of personal information. The 2025 European assessment likewise distinguished strong elements of the Czech digital ecosystem from unfinished tasks in infrastructure and enterprise adoption. Such constraints should not be interpreted as evidence that previous achievements were superficial, because complex innovation systems develop through unresolved trade-offs. They instead establish the policy and institutional conditions under which progress after 2025 must be judged.

Another difficulty concerns the measurement of national achievement within a deeply international system of knowledge production; a university research paper may involve contributors from several countries whose intellectual roles cannot reasonably be separated by nationality alone. A software enterprise may originate in Czechia, employ local developers, attract overseas finance and subsequently change its legal headquarters. A major computing facility may operate domestically while serving international users under shared governance arrangements. These differences make simple classifications of discoveries, products and infrastructure potentially misleading. This volume has therefore distinguished intellectual authorship, institutional affiliation, research location, corporate ownership and practical application wherever the evidence permits. It has also avoided treating participation in a

multinational programme as equivalent to originating all of that programme's results. Conversely, international collaboration should not conceal the independent contributions of researchers based at Czech institutions. Scientific quality requires reference to original publications, research methods and independently assessable results, while industrial quality requires attention to technological capabilities and sustained market performance. The credibility of the national historical narrative ultimately depends upon such distinctions more than upon claims of exclusive ownership or exceptionalism.

The experience of 1993–2025 also clarifies the relationship between digital sovereignty and international interdependence. No national research system of the Czech Republic's scale can independently provide every processor, cloud platform, algorithm, laboratory and specialist skill needed by contemporary computing. Meaningful autonomy instead requires the ability to formulate research priorities, develop technical expertise, protect essential infrastructure and participate effectively in shared international systems. European research networks and computing programmes expand opportunities precisely because they allow countries to contribute different capacities to collective projects. The development of domestic semiconductor competence and quantum research can strengthen this position without eliminating international technological dependencies. Similar reasoning applies to cybersecurity, where national institutions must cooperate with providers and research communities beyond their jurisdiction. Sovereignty must therefore be evaluated through operational resilience, informed choice and the capacity to retain knowledge rather than through unrealistic expectations of complete technological self-sufficiency. A system dependent solely on external products without domestic critical expertise remains vulnerable, even when it appears digitally advanced. A system that sustains strong research communities and dependable partnerships can exercise greater agency despite unavoidable international dependencies. Czech experience offers a practical illustration of this more relational understanding of technological independence.

The distinctive strength of the Czech model lies in the coexistence of several forms of innovation rather than in the dominance of a single technology; fundamental mathematicians produced concepts and methods whose significance can extend well beyond immediate applications; Computational linguists developed language resources and processing methods grounded in Czech linguistic scholarship. Engineers created dependable software tools, advanced visual systems, robotics methods and scalable computational solutions. Entrepreneurs translated selected capacities into software services, cybersecurity products, industrial systems and creative digital industries. Universities, Academy institutes and shared infrastructures sustained the human and technical foundations needed for these activities. European partnerships enlarged the range of research questions and markets that domestic actors could address. Their interaction was not always efficient or equally beneficial, and important gaps remained between research capability and enterprise adoption. Nevertheless, the national system developed multiple routes through which knowledge could become technically useful and socially relevant. This diversity is a stronger basis for long-term resilience than dependence upon a single company, research fashion or infrastructure investment. It is also the principal reason the Czech

experience is instructive for researchers studying technological change in other medium-sized European economies.

At the endpoint of 2025, Czech computer science and information technology had therefore reached a markedly different position from that of the early post-socialist period. International collaboration had become a normal condition of research rather than an exceptional opportunity available to selected institutions. National computing infrastructure had expanded from basic networking towards sophisticated systems for high-performance computing, distributed research and emerging quantum applications. Czech-origin companies had demonstrated that specialised digital products could compete outside the domestic market, although ownership and global market conditions continued to evolve. Public institutions had developed extensive electronic services while confronting the complex task of making separate systems trustworthy and interoperable. Established academic schools remained relevant through their capacity to educate researchers and reformulate scientific questions in changing technological environments. New strategic priorities in artificial intelligence, semiconductors and digital resilience extended these responsibilities into areas requiring particularly sustained investment. The outstanding challenge was no longer simply to gain access to modern technologies, but to determine where Czech institutions could contribute original knowledge and maintain durable capabilities. Success after 2025 would depend upon the combined quality of research, professional education, governance, public trust and cooperation with international partners. The central conclusion of this study is that Czech digital development represents the conversion of historical scientific continuity into a plural, internationally integrated innovation ecosystem whose achievements are substantial but never independent of its institutional and social foundations.

Chronological Timeline 1993–2025

Major Events in the Development of Czech Computer Science, Information Technology and the Digital Economy

This timeline identifies dated institutional, scientific, commercial, infrastructural and regulatory developments between the establishment of the Czech Republic and the end of 2025. Events originating before independence are treated as background rather than entered as independent milestones. The distinction between establishment, implementation, inauguration and subsequent operation is maintained where the chronology requires it.

Transition, market formation and the early Internet,1993–2003

Year / date	Category	Event and historical significance
1993 1 January	Institutional reform	The independent Czech Republic begins operating a national research framework. The former Czechoslovak Academy's Czech institutes continue in the Academy of Sciences of the Czech Republic, including its computing and information-science expertise.
1993	Software industry	Zoner is founded in Brno, initially developing vector-graphics software. Its trajectory illustrates the emergence of specialised Czech software producers in the new market economy.
1993 15 June	Research networks	The national CESNET academic backbone begins operation, linking Prague and Brno on a 64 kbit/s route and connecting university towns to a shared research network.
1994 1 September	Higher education	Masaryk University establishes the Faculty of Informatics, the first independent specialist faculty of its kind in the Czech Republic.
1994	Internet development	The first commercial Internet access initiatives emerge alongside the academic network, while Prague hosts the international INET'94/JENC5 meeting.
1995 1 July	Market liberalisation	Termination of an exclusive public-data-services licence opens the way for wider entry by commercial Internet service providers. The Internet gradually moves beyond the academic sector.
1996 6 March	Research infrastructure	Czech universities and the Academy establish the CESNET association, which takes over academic-

		network operation from the Czech Technical University in Prague.
1996	Internet infrastructure	The national Internet exchange NIX.CZ and the scientific-computing service MetaCentrum emerge, creating institutions for domestic traffic exchange and distributed research computation.
1996	Digital entrepreneurship	Ivo Lukačovič launches Seznam.cz as a Czech-language web directory, laying the foundations of an important domestically developed digital platform.
1997	Research networks	A 34 Mbit/s backbone linked to the European TEN-34 programme enters service, increasing the capacity of national academic communications.
1997	Software product	Seznam.cz introduces the full-text search tool Kompas, supporting searches containing Czech diacritics and illustrating early local-language search engineering.
1998	Internet governance	The CZ.NIC association is founded to administer the .cz country-code domain, providing institutional governance for national Internet naming.
1998	Digital services	Seznam.cz introduces its free e-mail service as domestic online portals expand from directories into everyday communication.
1999 1 March	University systems	Masaryk University launches its university-wide Information System, an early large-scale Czech example of electronic academic administration.
1999	Digital creative industry	Bohemia Interactive is established, developing a Czech studio centred on proprietary software and interactive real-time simulation.
1999	International networks	CESNET builds TEN-155 CZ as part of European backbone modernisation; disputes over telephone access costs simultaneously reveal barriers to mass Internet adoption.
2000	Research networks	CESNET begins building CESNET2 and deploys a 2.5 Gbit/s Prague–Brno connection, preparing for a new generation of research networking.
2000	Digital legislation	Act No. 227/2000 Coll. on electronic signatures creates a legal basis for recognised electronic authentication and communication.
2001	European infrastructure	CESNET2 connects to the trans-European GÉANT research network, strengthening international access to scientific collaboration and data exchange.

2001	Software export	Bohemia Interactive releases Operation Flashpoint: Cold War Crisis, demonstrating the international potential of Czech game engines and simulation software.
2002 1 January	Higher education	Brno University of Technology establishes its Faculty of Information Technology, separating specialist computing education from its predecessor department.
2002	Optical networks	CESNET advances dark-fibre network engineering and develops CzechLight technologies, reinforcing domestic capacity in optical research networking.
2003	Innovation ecosystem	The South Moravian Innovation Centre (JIC) is established in Brno as part of the regional innovation strategy, connecting entrepreneurship, research and public support.
2003	Internet protocols	Internet Protocol version 6 is deployed within the CESNET2 production backbone, anticipating the demand for a larger and more flexible Internet address space.

European integration and institutional consolidation, 2004–2010

Year / date	Category	Event and historical significance
2004 1 May	European integration	The Czech Republic joins the European Union, expanding access to research programmes, scientific mobility and technology-development partnerships.
2004	Research connectivity	CESNET participates in European grid research and launches academic-roaming services through eduroam, linking connectivity with shared research access.
2004	Software product	Zoner Photo Studio 7 develops the company's specialisation in digital photographic workflows and illustrates the diversification of Czech creative software.
2005	Network architecture	The CESNET2 backbone is upgraded with dense wavelength-division multiplexing and 10 Gbit/s channels for rapidly growing scientific traffic.
2005	Search technology	Seznam.cz launches an internally developed full-text search engine, maintaining local engineering capability rather than depending entirely on foreign providers.

2006	Cross-border networks	Academic networks in the Czech Republic, Austria and Slovakia are interconnected, supporting regional research data exchange and network resilience.
2007 28 March	Electronic government	The first Czech POINT contact site opens in Prague 13, initiating an assisted model for obtaining authenticated public-register documents.
2007	Research institutions	The Academy's Institute of Computer Science becomes a public research institution within a revised national legal framework for scientific organisations.
2008	Cybersecurity	CESNET establishes its incident-response capability, including the CSIRT.CZ team, while the eduID.cz identity federation strengthens trusted academic access.
2008	Digital government	Czech POINT expands from its pilot model to a wider public-service network, preparing the administrative infrastructure for secure electronic communication.
2009 1 July	Digital legislation / services	The information system of datové schránky (official electronic data boxes) begins operation under Act No. 300/2008 Coll., enabling legally recognised electronic delivery.
2009	Research computing	MetaCentrum is designated a national grid infrastructure, reinforcing distributed computational resources and access for researchers.
2010	Cybersecurity governance	CSIRT.CZ receives the status of national computer-security incident response team; CESNET is also included in the national research-infrastructure roadmap.
2010	Technology entrepreneurship	The JIC-linked StarCube start-up accelerator begins operating in Brno, supporting an emerging culture of early-stage technology ventures.

Supercomputing, cybersecurity and digitally enabled science, 2011–2020

Year / date	Category	Event and historical significance
2011 July	Supercomputing institutions	The IT4Innovations Centre of Excellence project is launched in Ostrava, beginning the construction of a national centre for high-performance computing and computational research.
2011	Optical research	CESNET demonstrates precise optical time transfer between Prague and Vienna, extending network research beyond routine data transmission.

2012 1 July	Electronic government	The Czech Basic Registers Information System enters production, permitting controlled exchange of authoritative reference data between public authorities.
2012	Network capacity	CESNET increases its major optical routes to 100 Gbit/s and expands distributed data-storage services for science.
2013 1 July	Academic institutions	The Czech Technical University establishes the Czech Institute of Informatics, Robotics and Cybernetics (CIIRC), creating a cross-disciplinary centre for intelligent systems.
2013	Supercomputing	The Anselm supercomputer is installed at IT4Innovations, giving Czech research teams access to new national-scale parallel computing resources.
2014 August	Supercomputing	The IT4Innovations research-centre building opens in Ostrava, consolidating computational laboratories, user services and the national supercomputing programme.
2014 29 August	Digital legislation	Act No. 181/2014 Coll. on Cyber Security is published, establishing a dedicated national regulatory framework; implementation begins in 2015.
2015 1 January	Cybersecurity law	The Cyber Security Act takes effect, introducing defined security obligations, incident reporting and oversight mechanisms for specified information systems.
2015 September	Supercomputing	IT4Innovations launches Salomon, a petascale supercomputer that significantly increases Czech capabilities in simulation, optimisation and scientific data processing.
2016 30 September	Corporate acquisition	Avast completes the acquisition of a controlling interest in AVG, combining two historically Czech antivirus brands in a globally oriented cybersecurity group.
2016	Research networking	The CESNET link to GÉANT reaches 100 Gbit/s, expanding capacity for international scientific data exchange.
2017 1 August	Cybersecurity governance	The National Cyber and Information Security Agency (NÚKIB) is established as an independent central authority, marking a new stage of state cybersecurity governance.

2017	Scientific connectivity	CESNET connects the ELI Beamlines research facility to national research-network infrastructure, supporting demanding experimental data flows.
2018	Research infrastructure	The Czech Republic joins the EuroHPC Joint Undertaking, embedding national supercomputing policy more deeply in European high-performance computing cooperation.
2018 25 May	Data protection	The European Union General Data Protection Regulation becomes applicable in Czechia, changing the compliance environment for public bodies and digital companies.
2018 3 October	Digital policy	The government approves the Digital Czechia strategy, aligning digital public administration, connectivity and the wider information society within a national programme.
2019 May	Artificial intelligence policy	The first Czech National Artificial Intelligence Strategy is issued, linking scientific research, competitiveness, business adoption and governance of intelligent systems.
2019 October	Supercomputing	Barbora enters operation at IT4Innovations alongside specialised computing systems for artificial intelligence, extending the range of available research architectures.
2019	Infrastructure partnership	CESNET, Masaryk University and VSB–Technical University of Ostrava prepare e-INFRA CZ as an integrated national research e-infrastructure.
2020	Research ecosystem	e-INFRA CZ begins operation, integrating CESNET, CERIT-SC and IT4Innovations across networks, computation and research data services.
2020	Digital rights	Act No. 12/2020 Coll. on the Right to Digital Services establishes a statutory framework for expanding digital interaction with public authorities.
2020	Public-service resilience	COVID-19 restrictions accelerate distance teaching and remote collaboration; CESNET and partner infrastructures expand services supporting universities and scientific work.

Advanced computing, technological sovereignty and new strategies, 2021–2025

Year / date	Category	Event and historical significance
2021	Supercomputing	The Karolina supercomputer enters service in Ostrava under the European EuroHPC programme, advancing large-scale modelling and artificial intelligence workloads.
2021	Quantum networking	e-INFRA CZ participants demonstrate inter-city quantum-key distribution, signalling research progress in security-oriented optical communications.
2022	Research networking	The upgraded national academic backbone receives the name CESNET3, expanding optical and data-service capabilities.
2022	Cybersecurity industry	The merger of Avast and NortonLifeLock creates Gen Digital, illustrating both the international reach of Czech-origin software brands and changes in their ownership structures.
2022	European research infrastructure	The LUMI supercomputer is inaugurated in Finland as a European resource in whose consortium the Czech IT4Innovations centre participates.
2023 1 April	Digital government	The Digital and Information Agency (DIA) begins operations and assumes responsibility for several core state services, including Czech POINT, the Citizen Portal and data boxes.
2023	Network modernisation	CESNET completes a major backbone upgrade permitting transmission at up to 400 Gbit/s per optical channel.
2024 January	Digital identification	The eDoklady mobile application is introduced as an electronic form of identification, initially accepted at selected central government bodies.
2024 24 July	Artificial intelligence strategy	The government approves the updated National Artificial Intelligence Strategy of the Czech Republic 2030, setting goals for research, adoption, skills and responsible implementation.
2024 10 October	Semiconductor policy	The National Semiconductor Strategy is approved to strengthen chip design, industrial capacity, skills and European supply-chain participation.
2025 7 April	Semiconductor research	The Czech Semiconductor Centre opens in Brno at Brno University of Technology, bringing academic, industrial and European chip-development initiatives closer together.

2025 June	Digital economy assessment	The European Commission's Digital Decade country report identifies strengths in mobile connectivity and skills alongside weaknesses in high-capacity fixed networks and business digitalisation.
2025 23 September	Quantum computing	The VLQ quantum computer is inaugurated at IT4Innovations in Ostrava under the LUMI-Q consortium; inauguration is distinguished from subsequent broad user access.
2025 October	Artificial intelligence infrastructure	A Czech AI Factory is included among new EuroHPC selections; the event marks project approval and development, not completion of an operational factory in 2025.

Major Czech Computer Science Institutions, Research Centres and IT Companies, 1993–2025

Section I

Universities, Research Institutes, Centres and Digital Infrastructures

Official name / location	Specialisation / website	Activities and historical significance, 1993–2025
Charles University — Faculty of Mathematics and Physics (Matematicko-fyzikální fakulta Univerzity Karlovy) Prague	Theoretical computer science; software systems; natural language processing; graphics mff.cuni.cz	Algorithms, formal methods, distributed software, language resources and doctoral research. Historical significance: An enduring Prague research school connecting mathematical theory with computer science and international scholarly networks.
Charles University — Faculty of Mathematics and Physics / Institute of Formal and Applied Linguistics (Ústav formální a aplikované lingvistiky) Prague	Computational linguistics and language technologies ufal.mff.cuni.cz	Prague Dependency Treebank, language annotation, machine translation and multilingual resources. Historical significance: Major Czech contribution to language data, syntactic annotation and reproducible language-technology research.
Czech Technical University in Prague — Faculty of Electrical Engineering (Fakulta elektrotechnická ČVUT) Prague	Artificial intelligence; robotics; computer vision; cybernetics fel.cvut.cz	Intelligent agents, autonomous navigation, perception, control and embedded systems. Historical significance: Anchored internationally connected Prague schools of perception, robotics and machine intelligence.
Czech Technical University in Prague — Faculty of Information Technology (Fakulta informačních technologií ČVUT) Prague	Computer science education; hardware and software technologies fit.cvut.cz	Security, computer architecture, algorithms, information systems and applied computing. Historical significance: Expanded specialised university computing education and research following its establishment in 2009.

Czech Institute of Informatics, Robotics and Cybernetics (Český institut informatiky, robotiky a kybernetiky, CIIRC) Prague	Cyber-physical systems; industrial AI; robotics ciirc.cvut.cz	Advanced manufacturing, intelligent control, automation and RICAIP research collaborations. Historical significance: Strengthened the connection between university computing research and industrial digital transformation.
Masaryk University — Faculty of Informatics (Fakulta informatiky Masarykovy univerzity) Brno	Formal verification; cybersecurity; databases; computational methods fi.muni.cz	Software verification, cryptographic security, similarity search, graphics and machine learning. Historical significance: Established in 1994 as the first specialised informatics faculty in Czechia and became a major Brno research centre.
Masaryk University — CERIT-SC / CERIT Scientific Cloud Brno	Scientific cloud and data-intensive research infrastructure cerit-sc.cz	Distributed computation, cloud services, storage and national e-infrastructure integration. Historical significance: Provided academic cloud capacities and contributed to e-INFRA CZ by 2020.
Brno University of Technology — Faculty of Information Technology (Fakulta informačních technologií VUT) Brno	Speech technology; formal methods; software engineering fit.vut.cz	Automatic speech recognition, multimedia analysis, embedded computing and verification. Historical significance: Faculty founded in 2002; advanced an influential Brno technology and research school.
Brno University of Technology — Faculty of Electrical Engineering and Communication (Fakulta elektrotechniky a komunikačních technologií VUT) Brno	Electronics; control; communications; embedded hardware feec.vut.cz	Signal processing, microelectronics, instrumentation and intelligent control. Historical significance: Linked digital systems research with engineering and industrial development in South Moravia.
VSB–Technical University of Ostrava — Faculty of Electrical Engineering and Computer Science (Fakulta elektrotechniky a informatiky	Computer science; engineering informatics; control fei.vsb.cz	Programming, information systems, computing, telecommunications and engineering applications. Historical significance: Provided the educational and institutional base for Ostrava's computing specialisation.

VŠB–TUO) Ostrava		
IT4Innovations National Supercomputing Center (Národní superpočítačové centrum IT4Innovations) Ostrava	High-performance computing; AI; quantum computing it4i.cz	Supercomputers, scalable algorithms, computational modelling, large-scale data analytics. Historical significance: Since 2013 has provided national supercomputing facilities and international research access.
Institute of Computer Science of the Czech Academy of Sciences (Ústav informatiky AV ČR) Prague	Fundamental informatics; computational methods cs.cas.cz	Algorithmic and mathematical foundations, modelling and cross-disciplinary computing. Historical significance: Inherited earlier Czechoslovak computing capacity and evolved into a fundamental research institution after 1993.
Institute of Information Theory and Automation of the Czech Academy of Sciences (Ústav teorie informace a automatizace AV ČR) Prague	Information theory; systems science; artificial intelligence utia.cas.cz	Statistics, signal and image processing, mathematical optimisation and control theory. Historical significance: Maintained a longstanding Academy school of mathematical information sciences and interdisciplinary automation.
Institute of Mathematics of the Czech Academy of Sciences (Matematický ústav AV ČR) Prague	Mathematical foundations and discrete research math.cas.cz	Logic, discrete structures, analysis and mathematical research underpinning computational methods. Historical significance: Sustained fundamental mathematical traditions relevant to Czech theoretical computing.
University of West Bohemia — Faculty of Applied Sciences (Fakulta aplikovaných věd ZČU) Plzeň	Computer science; speech; modelling fav.zcu.cz	Natural language and speech technologies, computer graphics, applied mathematics and cybernetics. Historical significance: Developed significant regional expertise in language technology and interdisciplinary computation.

Palacký University Olomouc — Faculty of Science (Přírodovědecká fakulta UP) Olomouc	Theoretical and applied computer science; fuzzy logic prf.upol.cz	Knowledge representation, logical systems, computational methods and advanced informatics education. Historical significance: Supported internationally known research in formal fuzzy logic and computational reasoning.
Technical University of Liberec — Faculty of Mechatronics, Informatics and Interdisciplinary Studies (Fakulta mechatroniky, informatiky a mezioborových studií TUL) Liberec	Mechatronics; embedded systems; industrial computing fm.tul.cz	Intelligent sensors, automation, control and interdisciplinary engineering informatics. Historical significance: Connected regional engineering traditions with digital production and intelligent systems.
University of South Bohemia — Faculty of Science (Přírodovědecká fakulta JU) České Budějovice	Applied informatics; computational science prf.jcu.cz	Computer science education, software methods, computational biology and information systems. Historical significance: Strengthened regional training and cross-disciplinary digital research in South Bohemia.
Tomas Bata University in Zlín — Faculty of Applied Informatics (Fakulta aplikované informatiky UTB) Zlín	Applied informatics; automation; security fai.utb.cz	Intelligent control, system modelling, industrial informatics and information security. Historical significance: Linked the Zlín industrial region to research and education in modern information technology.
CESNET, association of legal entities (CESNET, zájmové sdružení právnických osob) Prague	Academic networking; optical communications; research e-infrastructure cesnet.cz	National scientific backbone, identity management, data storage and advanced network research. Historical significance: Founded in 1996; became a key national and European research-network operator.
e-INFRA CZ national research e-infrastructure Prague / Brno / Ostrava	Integrated research networks, cloud and HPC e-infra.cz	Shared CESNET, CERIT Scientific Cloud and IT4Innovations services. Historical significance: From 2020 linked complementary national computing and data facilities into a common research infrastructure.

LINDAT/CLARIAH-CZ research infrastructure Prague and partner institutions	Digital language and humanities resources lindat.cz	Corpora, annotation software, language models and research-data access. Historical significance: Connected Czech language technologies and digital humanities with European research infrastructures.
CESNET — MetaCentrum Distributed; coordinated from Prague	Distributed academic computing metacentrum.cz	National computational grids, user allocation and scientific computing services. Historical significance: Gave research groups access to shared computation beyond individual university laboratories.
CZ.NIC, z. s. p. o. Prague	National internet domain infrastructure nic.cz	Administration of the .cz domain; DNS research, security and internet education. Historical significance: Founded in 1998, it became central to the stability and development of Czech internet infrastructure.
NIX.CZ, z. s. p. o. Prague	Internet exchange and interconnection nix.cz	Peering and national and international internet traffic exchange. Historical significance: Founded in 1996; reduced dependence on external routing and enhanced Czech connectivity.
National Cyber and Information Security Agency (Národní úřad pro kybernetickou a informační bezpečnost, NÚKIB) Brno	National cybersecurity administration nukib.gov.cz	Cybersecurity policy, regulatory oversight, coordination and critical systems protection. Historical significance: Established in 2017; strengthened national cyber governance and digital resilience.
Czech National Computer Security Incident Response Team (CSIRT.CZ) Prague	Coordinated incident response csirt.cz	Information sharing, incident management and awareness for Czech networks. Historical significance: Created a national coordination capability between internet operators, technical experts and public stakeholders.

South Moravian Innovation Centre (Jihomoravské inovační centrum, JIC) Brno	Regional innovation and technology entrepreneurship jic.cz	Start-up incubation, business support and university–industry links. Historical significance: Established in 2003; became an important intermediary in the Brno innovation ecosystem.

Section II

IT Enterprises, Digital Product Developers and Innovation Organisations

Official name / location	Specialisation / website	Activities and historical significance, 1993–2025
Software602 Prague	Office software; electronic documents 602.cz	Office suites, document workflows and business applications. Historical significance: A characteristic early post-socialist Czech software producer and later enterprise digital-services provider.
ABRA Software Prague	Enterprise resource planning abra.eu	Accounting, enterprise management and business information systems. Historical significance: Helped build a domestic market for commercial enterprise software.
Zoner Software Brno	Digital imaging; software publishing zoner.com	Zoner Photo Studio and image management products. Historical significance: Illustrates long-term Czech software product development and export-facing digital creativity tools.
Seznam.cz Prague	Internet search; media; digital advertising firma.seznam.cz	Search, Mapy.cz, news, email and online services. Historical significance: Founded in 1996; built one of the most significant Czech-language internet platforms.
Avast / ALWIL Software Prague	Endpoint security; antivirus software avast.com	Consumer security, threat analytics, mobile and network protection. Historical significance: Grew from Czech-

		origin security development into a global business; merged with AVG in 2016.
AVG / Grisoft Brno / Prague	Antivirus and internet security avg.com	Consumer and business endpoint-protection products. Historical significance: A second major Czech-origin cybersecurity firm; acquired by Avast in 2016.
Gen Digital Prague / Tempe, Arizona (international)	Consumer digital security gendigital.com	Portfolio of cyber safety brands including Avast and AVG. Historical significance: Formed through the 2022 combination of NortonLifeLock and Avast; illustrates the international restructuring of Czech-origin assets.
Y Soft Brno	Enterprise document and print management ysoft.com	Digital workflows, print management and enterprise software. Historical significance: A Brno-based company demonstrating international expansion of specialised business technologies.
GoodData Prague / San Francisco	Business intelligence; cloud analytics gooddata.com	Analytics platforms and data-driven enterprise solutions. Historical significance: Czech-founded international product enterprise bridging Prague engineering and world markets.
Keboola Prague	Cloud data operations and integration keboola.com	Data pipelines, orchestration and analytics engineering. Historical significance: Represents Czech-origin platforms for enterprise data management and international cloud services.
Ataccama Prague / Toronto	Enterprise data quality and governance ataccama.com	Data integration, master data management and data governance. Historical significance: Expanded Czech-founded enterprise data software into international markets.
Kiwi.com Brno	Travel technology; digital platforms kiwi.com	Flight-search algorithms, virtual interlining and travel booking technology. Historical significance: Founded in 2012; illustrates internationally scaled algorithmic online intermediation.

Productboard Prague / San Francisco	Product management software productboard.com	Enterprise product discovery, prioritisation and roadmaps. Historical significance: Czech-founded technology start-up that scaled a subscription software platform globally.
Mews Prague / international offices	Hospitality cloud software mews.com	Property management, hotel operations and payments integrations. Historical significance: Czech-rooted company demonstrating international growth in specialised software-as-a-service.
Rossum Prague	Artificial intelligence; document automation rossum.ai	Machine-learning document extraction and business workflow automation. Historical significance: Illustrates commercialisation of Czech AI expertise in global business processes.
Rohlik Group Prague	E-commerce; grocery logistics rohlik.group	Online retail platforms, warehouse software and fulfilment optimisation. Historical significance: Demonstrates the links between software engineering, logistics and cross-border digital commerce.
JetBrains (Prague development operations) Prague / international	Software development tools jetbrains.com	Integrated development environments and developer productivity software. Historical significance: International company with a significant Prague engineering presence; not classified as Czech-founded.
Red Hat Czech (Brno development centre) Brno	Open-source enterprise software redhat.com	Linux, cloud infrastructure, middleware and developer engineering. Historical significance: A major international research and development employer contributing to Brno's software ecosystem.
Codasip Brno / international offices	Processor design and semiconductor intellectual property codasip.com	RISC-V processor intellectual property and hardware design tools. Historical significance: An example of Czech-rooted design capabilities in internationally distributed chip engineering.

onsemi (Rožnov operations) Rožnov pod Radhoštěm / international	Semiconductors; power electronics onsemi.com	Semiconductor manufacturing and engineering at Rožnov. Historical significance: Foreign-owned production base with enduring Czech technical skills and strategic investment plans during 2024–2025.
Bohemia Interactive Prague and other Czech sites	Video games; military simulation technology bohemia.net	Arma series, game engines and simulation products. Historical significance: Czech developer with global reach and advanced real-time simulation capabilities.
SCS Software Prague	Video games; vehicle simulation scssoft.com	Euro Truck Simulator, American Truck Simulator and proprietary game technologies. Historical significance: Export-oriented developer demonstrating specialised simulation and durable product support.
Amanita Design Brno / Prague	Independent games; interactive art amanita-design.net	Samorost, Machinarium, hand-crafted visual design and interactive storytelling. Historical significance: International recognition for Czech digital aesthetics and original multimedia experiences.
Warhorse Studios Prague	Historical role-playing games warhorsestudios.cz	Kingdom Come: Deliverance series; open-world simulation and historical production. Historical significance: Prominent export-facing Czech game studio combining software engineering and cultural production.
Beat Games Prague	Virtual-reality entertainment beatsaber.com	Beat Saber, motion-based virtual-reality gameplay. Historical significance: Czech-founded studio acquired by Facebook in 2019; illustrates global demand for original interactive products.
Wube Software Prague	Simulation and strategy games factorio.com	Factorio and optimisation-intensive simulation mechanics. Historical significance: Independent Czech studio with international reputation for engineering-focused interactive systems.

Czech Game Developers Association (Asociace českých herních vývojářů) Prague / national	Industry representation and statistics gda.cz	Sector monitoring, education, advocacy and international promotion. Historical significance: Founded in 2018; supplied an organised industry voice and a basis for sector-wide analysis.
CzechInvest Prague / regional offices	Investment promotion; start-up development czechinvest.gov.cz	Technology investments, entrepreneurship assistance and sector mapping. Historical significance: Public investment agency facilitating international investment and support for Czech technology companies.

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