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Physical aspects of the IT industry: From software architectures to cyber-physical systems

Taras Liashuk*

PhD in Physics and Mathematics, Senior Lecturer
Rivne State University of Humanities
33028, 12 Stepana Bandery Str., Rivne, Ukraine
https://orcid.org/0000-0002-2242-7537

Abstract. The functioning of modern computing systems is based on a complex interconnection of hardware and applied physical phenomena. The relevance of the study was determined by the fundamental dependence of technological innovations in the IT industry on the laws of physics, which simultaneously defined both limits (e.g. quantum tunnelling in nanometre-scale transistors) and new opportunities (e.g. quantum superposition in qubits). The aim of the work was to analyse the interconnection of fundamental physical laws with the hardware-software architecture of computing systems and to determine directions for future development. The methodology of the study was based on a systematic approach, including content analysis of high-quality scientific data, structural-functional analysis of physical clusters, and theoretical synthesis of interdisciplinary connections, supported by logical-graphical modelling. The main results of the study revealed that quantum mechanics and thermodynamics set the physical limits for transistor miniaturisation and managed the thermal regime of microchips, while optics was the foundation for high-speed data transmission and microchip lithography. Classical mechanics and electrodynamics ensured the functioning of cyber-physical systems, including automated control systems, robotic complexes, and wireless communication infrastructure. It was analysed that molecular physics and the modelling of nanoscale structures played a crucial role in the design of new semiconductor materials and the prediction of component durability based on appropriate computer-physical models. It was shown that nuclear and atomic physics played a key role in ensuring the radiation hardness of electronics and were considered a potential power source for highly autonomous computing complexes. Particular attention was paid to promising areas, specifically superconductivity, quantum computing, and quantum cryptography. The practical value of the work lies in forming a comprehensive perspective on the physical foundations of computing systems, which was critically important for computer and software engineers, and scientists when developing new materials, designing high-performance and energy-efficient microchips, and creating reliable autonomous and quantum computing systems

Keywords: computational physics; nanotechnology; computer modelling; planar technology; quantum computing; energy efficiency; signal integrity

INTRODUCTION

Global technological progress is characterised by the rapid approach of information and computing systems (ICS) to critical physical limits, demanding an integrated approach to modelling and practical implementation of materials, thermodynamics, and high-frequency electrodynamics at the nanoscale. The necessity for further transistor miniaturisation, enhanced energy efficiency, and the development of novel software architectures requires a deep understanding of subatomic processes, where computer modelling serves as the

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*Corresponding author(taras.liashuk@rshu.edu.ua)

foundation for industrial prototyping, optimising device behaviour, and ensuring the structural integrity of final hardware-software solutions. Given this, the relevance of the study lies in the necessity to systematise the fundamental physical principles underlying the development of innovative information technology (IT) solutions, including enhancing thermal efficiency, ensuring high-speed signal integrity, and developing post-silicon computing paradigms. The objective of the work was to conduct comprehensive analysis of the influence of various fields of computational physics (CP) on the formation of ICS architecture.

One of the most acute problems is overcoming the physical limits of transistor miniaturisation. In the work of Y. Cai *et al*. (2020), it was shown that the study of nanoscale semiconductors (SCs) required the application of the laws of quantum mechanics (QM) to predict electron behaviour. In the works of P. Kumari (2024) and A. Mubashr (2025), dedicated to the physical limits of miniaturisation and quantum tunnelling, the necessity of transitioning to new materials, whose properties were modelled using Ab Initio methods (quantum chemistry), was emphasised. The issue of thermal regime control for high-performance chips, which was a direct application of thermodynamics, was actively investigated in the context of two-phase cooling in the work of N. Mohammed *et al*. (2025). The analysis demonstrated that, in liquid cooling, the maximum server temperature diminished to 65°C, and power usage effectiveness improved from 2 in the air cooling system to 1.01 in liquid cooling. The application of copper coating resulted in a 13% enhancement in the gradual temperature distribution among servers, especially in high-power servers, and eliminated hottest spots by decreasing the maximum temperature. However, the simulation indicated a comparatively modest temperature improvement of 8% when coating low-power servers. Continuing the topic, the reliability assessment of systems under thermal loads was also considered by H.-S. Kim *et al*. (2025). It was found that the fatigue life and fatigue crack type (solder joint crack or Cu trace crack) were influenced and changed significantly by package geometry and solder joint materials. The predicted fatigue life and crack type from Finite Element Analysis (FEA) agreed well with the experimental results.

In the field of communications, the study by D. Kalavathi (2025) was focused on optimising signal integrity and electromagnetic compatibility through numerical modelling of electrodynamics for high frequency ranges. A comprehensive approach to modelling and optimising electromagnetic interference was developed using deterministic and statistical methods alongside 3D electromagnetic solvers. Advanced optimisation techniques, including Genetic Algorithms and Machine Learning-based predictive models, were employed to minimise electromagnetic interference while ensuring system performance. The effectiveness of the proposed design methodologies was confirmed through experimental validation using hardware prototypes and electromagnetic interference test setups. Further development of optoelectronics and LiDAR (Light Detection and Ranging) systems was demonstrated in the study by P. Pendse (2024), which was based on the improvement of optics and sensors, being critically important for autonomous vehicles.

The most ambitious areas, such as quantum computers based on superconducting qubits, were a direct synthesis of QM and superconductivity, highlighted in the work O. Ezratty (2023). A great variety of technological options was demonstrated, explaining how superconducting qubit chipsets were manufactured, describing challenges related to qubit control via classical electronics, and analysing ways to improve their accuracy and optimise their energy footprint. Also relevant were studies of the impact of cosmic radiation (nuclear physics) on the durability and reliability of electronics, which had direct application in space technology and was shown by the authors F.N.U. Naveed & J. Dix (2025). This paper presented a radiation-hardened 4-bit flash analogue-to-digital converter implemented in a 22 nm fully depleted silicon-on-insulator process for high-reliability applications in radiation environments. The analysis of scientific and technical literature confirmed the decisive role of the interconnectedness of physics and IT, demonstrating that fundamental physical limitations and capabilities determined the vectors of development for ICS hardware and software architecture. Recent studies in the most advanced, yet most problematic, areas of CP were reviewed. The research problematics were focused on the fact that traditional engineering design approaches increasingly encountered quantum and relativistic effects (Hidalgo, 2022), which were previously ignored. This necessitated the integration of numerical methods for accurate modelling (Camiola *et al.*, 2025).

The scientific novelty of the work consisted in the systematisation and integrative representation of the role of fundamental physical disciplines, spanning the range from classical to quantum physics, to create a unified, interdisciplinary concept for the functioning and development of key technological areas within the IT industry. Given the interdisciplinary nature of the identified scientific problems and the lack of their comprehensive unification, the aim of the work was to generalise and integrate knowledge regarding the key physical phenomena underlying the architecture, materials science, reliability, and functional capacity of modern ICS.

MATERIALS AND METHODS

The methodology of this research was based on a comprehensive interdisciplinary approach aimed at the systematisation and integration of fundamental physical laws within the context of the development and functioning of modern ICS. To achieve the set objective, a multi-stage research strategy was employed, which included the selection, critical analysis, and synthesis of high-quality scientific data at the intersection of CP and IT. At the first stage, a systematic literature search and data collection process was carried out. The information base of the study was formed using reputable international scientometric databases, including Scopus, Web of Science, IEEE Xplore, Google Scholar, and others. The data collection was specifically focused on journals and monographs specialising in IT and physics, particularly those exploring their deep interconnection. The search depth was primarily focused on the period between 2020 and 2025 to ensure the relevance of the data regarding the latest technological paradigms, such as 22 nm fully depleted silicon-on-insulator processes, extreme ultraviolet lithography (EUV), and superconducting quantum computing. The selection of sources was performed based on keyword queries, including "quantum effects in semiconductors", "thermal management in high-performance computing", "signal integrity in gigahertz ranges", "post-silicon computing paradigms", and others. At the second stage, the method of content analysis and critical evaluation was applied to the selected scientific materials. Each source was analysed for its contribution to the understanding of how specific physical phenomena (e.g., quantum tunnelling, thermal conductivity, or electromagnetic interference) influence the architecture and reliability of hardware and software solutions. Special attention was paid to identifying "bottlenecks" where traditional engineering approaches encountered fundamental physical limits, such as the diffraction limit in optics or the sub-threshold swing in transistors.

The third stage involved the use of a systemic approach and structural-functional analysis to create a unified interdisciplinary concept. Fundamental physical disciplines were categorised into six key clusters: classical and relativistic mechanics, molecular physics and thermodynamics, electricity and magnetism, optics, QM, and atomic and nuclear physics. For each cluster, the direct application in IT was identified, ranging from the mechanical reliability of server enclosures to the quantum-mechanical modelling of qubits. This allowed for the transition from a fragmented description of physical effects to an integrated model of ICS functioning as a complex physical-technical system. To ensure the clarity of the proposed conceptual framework, a method of logical-graphical modelling was employed. This involved the structural mapping of causal relationships between physical laws and IT hardware parameters, resulting in the creation of integrated diagrams that synthesise complex interdisciplinary data into a coherent visual format.

At the final stage, the method of theoretical synthesis and generalisation was utilised to formulate the conclusions of the study. Comparative analysis was used to evaluate different modelling methods; specifically, FEA was identified as the most effective for large-scale mechanical and thermal simulations due to its computational efficiency, whereas Density Functional Theory (DFT) provided superior accuracy for predicting the atomic properties of new SC materials (e.g., 2D Janus LiMSSe), despite its significantly higher computational resource requirements. The integration of the obtained data was carried out to define the most promising vectors for the future development of the IT industry, including quantum cryptography and energy-efficient superconducting electronics. Thus, the applied complex of theoretical and analytical methods ensured the validity and comprehensiveness of the formed interdisciplinary vision.

RESULTS AND DISCUSSION

The obtained results presented a systematised analysis of the fundamental and applied areas of CP, detailed the discussion of their foundational principles and specific examples of application in the design, functioning, and development of modern ICS and their hardware and software architecture. Classical mechanics, based on Newton's laws, constitutes a vital foundation for CP by providing the mathematical apparatus for the numerical modelling of the dynamics and evolution of physical systems over time. Through the numerical integration of differential equations of motion, ICS can accurately reproduce the complex behaviour of objects ranging from nanoparticles to astronomical macro-bodies. In the IT industry, mechanics is essential for hardware reliability and real-world simulation, powering physical engines in video games and ensuring precision in high-tech manufacturing, such as the design of moving parts in hard drives or robotic systems.

One of the primary areas of application is hardware design, which focuses on the laws of dynamics, statics, and the strength of materials to ensure the reliability and durability of physical components. The mechanical reliability of enclosures and printed circuit boards (PCBs) is achieved through the principles of statics, where CP utilises the Finite Element Method (FEM) to analyse stresses and deformations. This allows for modelling how electronic boards and fastenings react to external forces, such as impacts or drops, as well as internal loads caused by temperature fluctuations. Furthermore, engineers had to model vibrational resistance to identify and avoid dangerous resonant frequencies that could lead to the failure of solder joints, a factor particularly critical for server equipment and mobile transport devices (Gharaibeh & Gharaibeh, 2023). The dynamics of high-speed moving parts in IT devices also require the direct application of Newtonian laws and kinematics. In Hard Disk Drives (HDDs), CP models the dynamics of the read/write head, which must be positioned over a magnetic platter at distances of less than 1 μm at high speeds; such simulations helped minimise vibrations and deviations that could could data errors (Chen *et al.*, 2025). Similarly, mechanics is used in optical drives (CD/DVD/Blu-ray) to model lens and laser mechanism movements for precise focusing, as well as in printers and plotters to ensure the reliability of paper feed systems and electric motors.

The principles of mechanics are further extended to Microelectromechanical Systems (MEMS), which underpin the operation of smartphones, unmanned aerial vehicles (UAVs), and navigation systems. Sensors such as accelerometers and gyroscopes measure acceleration and angular velocity using the principle of inertia from Newton's first law. In these devices, CP modelled the movement of microscopic mechanical masses that changed their physical configuration under external forces, which resulted in measurable changes in quantities such as electrical capacitance (Kempe, 2011). Molecular and N-body dynamics also rely on numerical methods within CP, utilising Newton's second law to model systems consisting of a large number of interacting objects. In molecular dynamics, the motion and interaction of atoms and molecules are calculated using intermolecular potentials, enabled the study of material properties or protein folding (Pal & Ray, 2020). Conversely, N-body dynamics is applied to larger systems where interactions are described by gravitational or electrostatic forces, which allowed researchers to predict the behaviour of systems, such as electron beam collisions in plasma, that are nearly impossible to investigate through physical experiments (Patsis & Okalidis, 2025).

In the field of robotics and automated systems, classical mechanics serves as the basis for control algorithms that ensure precise task execution. This involves kinematic calculations to describe manipulator motion without considering forces, as well as dynamic analysis that accounts for gravity, friction, and inertia. Computing systems had to numerically determine the torque and power required for each motor to achieve smooth and energy-efficient movement (Kadri *et al.*, 2025). Furthermore, virtual simulation allowed for the creation of precise digital twins of robots to plan trajectories and model collisions using the laws of momentum and energy conservation (Wang *et al.*, 2022). For mobile systems such as UAVs, mechanics is constantly used to calculate the centre of mass and stability, which allowed control systems to instantaneously compensate for external factors like wind or tilt, ensuring balance and preventing loss of stability (Yunping *et al.*, 2018). Realism in computer graphics and game engines is achieved through specialised physical engines that utilise mechanical principles for real-time behaviour modelling. These engines constantly calculate forces such as gravity, friction, and air resistance, applying conservation laws to model complex interactions like object collisions, explosions, and fluid dynamics (Sung *et al.*, 2025).

Finally, while most engineering solutions rely on classical mechanics, certain IT systems involving space and high speeds must account for Einstein's theory of relativity. Global Navigation Satellite Systems (GNSS), such as Global Positioning System (GPS), require constant signal adjustments based on relativistic effects. Special relativity accounts for the high speed of satellites (≈ 14,000 km/h) causing onboard clocks to run slower, while general relativity accounts for the weaker gravitational field causing them to run faster. If ignored, these effects would lead to positioning errors exceeding 10 km per day; therefore, computational components numerically calculated these relativistic corrections to maintain the precision required for modern navigation (Ayso & Kahveci, 2025).

Molecular physics and thermodynamics constitute an indispensable foundation for CP, as they govern all energetic, thermal, and structural processes in IT equipment at both micro- and macroscopic levels. These branches of physics provide the mathematical apparatus, based on statistical laws and the principles of energy conservation, for modelling the behaviour of atoms and molecules. Such modelling is critically important for understanding the thermal balance, efficiency, and longevity of systems. In the IT industry, this allows engineers not only to comply with strict thermal limits for high-performance chips but also to reproduce nanotechnological processes in manufacturing, where minute changes in temperature and atomic movement are crucial for the functionality of the final ICS.

The application of these principles is most evident in nanotechnologies and the manufacturing of SC components. Planar technology remains the primary method for the mass production of SC elements, including processors and microcontrollers. Its continuous improvement is driven by Moore's Law, which necessitates the relentless shrinking of component sizes. Key stages such as lithography, oxidation, and dopant diffusion are governed by thermodynamic variables. For instance, oxidation controls the growth of thin silicon dioxide layers at high temperatures, serving as either a mask or a dielectric gate in MOSFET transistors. The creation of p-n junctions depends on the thermal diffusion of alloying elements within the silicon crystal. By utilising kinetic theory and diffusion models, CP enables the simulation of how dopant atoms distribute within the crystal lattice under high temperatures, allowing for precise control over the depth and concentration profiles that determined electrical characteristics (Martin-Bragado *et al.*, 2006).

Furthermore, molecular physics and thermodynamics are central to the development of cooling systems and thermal design. CP employs energy laws, such as the Joule-Lenz law and the laws of thermodynamics, alongside numerical methods like FEA to create models that optimise processor architecture for reduced heat generation. In high-performance environments, including data centres and mobile devices, numerical simulations of thermal conductivity, convection, and radiation are used to model temperature field distributions. This allows for the optimisation of cooling elements such as thermal pastes, radiators, and heat pipes, the latter of which relied on the physical phenomena of evaporation and condensation to ensure efficient heat dissipation (Tari & Yalcin, 2010).

The search for new materials also relies heavily on materials science and numerical testing of innovative substances. Researchers sought materials with exceptional thermal conductivity, such as graphene or diamond films, to enhance heat dissipation in high-performance computing (Chen *et al.*, 2022). Active research is also focused on SC composites like Gallium Nitride (GaN) and Silicon Carbide (SiC) for power electronics, which maintain superior electrical characteristics at elevated temperatures. Additionally, molecular physics principles are applied to optimise thermal interface materials and develop next-generation memory technologies, such as Resistive Random-access memory (RRAM) and Ferroelectric RAM (FRAM), where the switching of atomic or molecular states is fundamental to data storage. Finally, the principles of molecular physics and thermodynamics underpin the operation of various sensors within SMART systems and the Internet of Things (IoT). Temperature measurement is frequently based on changes in electrical resistance or thermoelectric effects resulting from variations in the intensity of atomic thermal motion. Similarly, gas sensors utilise chemical reactions that generate heat or changes in conductivity upon the adsorption of gas molecules (Goel *et al.*, 2023). Pressure sensors may also employ the thermodynamic properties of gases or the effects of mechanical deformation on a material's electrical properties, further demonstrating the integration of molecular physics into modern monitoring systems.

Electricity and magnetism serve as the fundamental language of ICS, as all processes of information transfer, storage, and processing occur through electric fields, currents, and electromagnetic waves. CP utilises Maxwell's equations and derivative laws, such as those formulated by Ohm, Coulomb, and Faraday, for the numerical modelling of signal propagation, antenna design, data integrity analysis, and interference prevention. Precise modelling and prediction of electromagnetic phenomena are essential for ensuring high speeds, reliability, and the continued miniaturisation of modern electronics. Figure 1 presents the hierarchy of abstraction layers in computing systems, demonstrating the sequential transformation of fundamental physical processes in SCs into logical operations and high-level software.

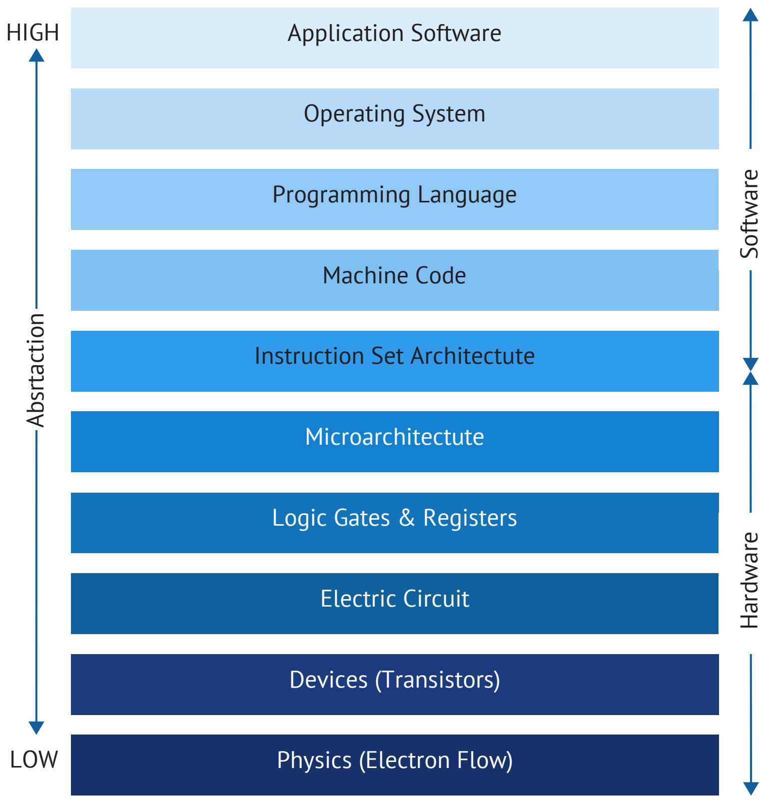

Figure 1. Layers of abstraction in computer systems

Source: compiled by the author

A critical area of application is the maintenance of signal and power integrity. In modern high-speed computers, where switching speeds reach the gigahertz range, electrical signals behave as electromagnetic waves on transmission lines. Consequently, modelling these lines was vital to prevent internal phenomena such as signal reflection and dispersion, which could degrade data quality (Jin *et al.*, 2004). This ensures that electrical pulses arrive at the receiver on time and without distortion. Similarly, power integrity is modelled to ensure the correct operation of inductive elements, such as coils and transformers, and to facilitate noise filtration through capacitors, maintaining the voltage stability required for reliable chip operation.

Furthermore, electricity and magnetism provide the indispensable foundation for data storage across various media (Ma, 2025). In electrical storage systems, such as Dynamic RAM (DRAM), information is stored as an electric charge in microscopic capacitors, with electrostatics being used to model rapid read/write cycles. Static RAM (SRAM) utilises transistor flip-flops, where electrodynamics describes the ultra-fast switching of currents. For non-volatile storage, such as Flash memory (SSD, EEPROM, EPROM), information is maintained as a charge trapped in a transistor's floating gate, where programming occurs through controlled electric fields that enable electron tunnelling. Emerging technologies, including FRAM and RRAM, use electric fields to change material polarisation or voltage to form conductive filaments, respectively. Magnetic storage remains equally significant; in HDDs, data is encoded via the magnetisation direction of microscopic areas on platters, a process optimised through CP modelling of magnetic fields and magnetoresistive effects. An equally important task in CP is ensuring electromagnetic compatibility and shielding, which allows for the management of undesirable radiation and the susceptibility of devices to external interference. As every electronic device is a potential source and receiver of electromagnetic waves, numerical methods were employed to design effective shielding (Morales *et al.*, 2023). This shielding was based on the mechanisms of reflection by highly conductive metals and absorption by materials with specific dielectric or magnetic losses. Such modelling guaranteed the uninterrupted operation of ICS, from mobile gadgets to complex cyber-physical systems, even in environments with high electromagnetic noise.

Wireless communication technologies, including Wi-Fi, Bluetooth, and 5G/6G, rely entirely on the transmission and reception of electromagnetic waves, with electrodynamics providing the only theory capable of describing antenna operation. CP was used to model field distribution around miniature antennas, optimising radiation patterns and impedance matching based on the electrical and magnetic properties of the structure (Basherlou *et al.*, 2025). Moreover, the introduction of new frequency spectra by engineers ensures the innovativeness and reliability of global communication technologies. Finally, reliable and autonomous power sources are critical for mobile and high-performance systems (Rasolomampionona & Kłos, 2023). CP applies the laws of electrodynamics and thermodynamics to model the electrochemical processes within Li-Ion batteries, enabling the optimisation of capacity, charging speed, and service life. Additionally, the operation of solar cells, used in autonomous IoT sensors and robotics, is based on the photoelectric effect. Here, electrodynamics and optics are utilised to model photon absorption and current generation in SC layers, allowing engineers to maximise energy conversion efficiency and develop flexible power sources.

Optics is a fundamental field of physics that studies the nature of light and its interaction with matter, providing the technological foundation for high-speed data transmission, high-precision manufacturing, and visual information gathering. CP utilises the laws of geometric and wave optics, including reflection, refraction, diffraction, and interference, for the numerical modelling and implementation of complex optical-physical systems. This enables engineers not only to overcome the geometric limitations of miniaturisation in microelectronics but also to create efficient high-performance networks and human-machine interfaces. A primary application of these principles is optical lithography, which is a fundamental process in the manufacturing of microprocessors and memory. This technology operates on the laws of wave optics, using diffraction and interference for the ultra-precise transfer of complex circuit patterns from a photomask onto a silicon wafer. As transistor sizes shrink towards the nanometre scale, as dictated by Moore's Law, the diffraction limit becomes a critical physical boundary. To overcome this, computer engineering employed complex wave optics modelling in the development of innovative systems such as immersion lithography and EUV, which ensured the resolution necessary for further component miniaturisation (Bakshi *et al.*, 2017).

Optoelectronic data transmission represents another vital area, encompassing the conversion of electrical signals into light signals to form the basis of high-speed communication. Fibre-optic networks, which underpin the modern internet and data centres, rely on the phenomenon of total internal reflection at the boundary between the fibre core and cladding. Optics is used to model dispersion and signal loss in long-distance lines, maximising transmission speeds. Beyond telecommunications, fibre optics is utilised in high-speed peripheral connections such as HDMI 2.1 and USB 4, as well as in avionics, space technology, and industrial SMART-networks. Furthermore, optical fibres serve as distributed sensors for monitoring large-scale infrastructure; by analysing how light propagation is affected by external influences, these systems can measure temperature, vibration, and strain in bridges, pipelines, and deep boreholes. The effective operation of these networks also requires the modelling of optical signal generators, such as lasers and LEDs, alongside photodetectors for signal reception (Kim, 2017).

The development of sensors and cameras also relies heavily on optical principles. Geometric optics is used to design lenses and microlens arrays, which are the foundation of computer vision systems in smartphones, UAVs, and autonomous transport. Additionally, LiDAR technologies act as optical distance sensors, relying on the laws of light propagation to measure the time-of-flight of laser pulses. These systems are crucial for 3D scanning and the navigation of autonomous mobile robotics (Zhou, 2022). Finally, optics is essential for the design of displays and immersive interfaces. In LED and LCD screens, optical modelling optimises brightness, colour accuracy, and viewing angles by analysing the interaction of light with liquid crystals or organic materials. For augmented and virtual reality (AR/VR), optical systems consisting of specialised lenses and prisms are indispensable for the correct display of images on screens positioned close to the eyes. Geometric optics allows for the accurate modelling of distortions and vision correction, ensuring a realistic and comfortable user interface (Song & Wu, 2024).

QM serves as a primary foundation for the modern IT industry, providing the theoretical framework to explain the behaviour of matter at atomic and subatomic levels. Without accounting for quantum effects, such as discrete energy levels and wave-particle duality, the functioning of SC materials – from which all transistors, processors, and memory are constructed – would be impossible. CP utilises quantum principles to model the band structure of materials and the behaviour of electrons in nanoscale structures, effectively defining the physical limits and capabilities of modern computing. While advanced areas such as quantum computing and cryptography remain promising, their full realisation represents a significant technological challenge for contemporary engineering. The understanding of SC and transistors is deeply rooted in QM, which explains how conductivity depends on band structures and how doping creates charge carriers. Modelling based on the Schrödinger equation allowed engineers to predict electron flow in MOSFET transistors, which are the basic building blocks of microchips (Cheng *et al.*, 1999). As transistor sizes shrink to the nanometre level, undesirable quantum effects, such as quantum tunnelling, emerge. This phenomenon describes the probability of an electron overcoming thin dielectric barriers even when its energy is lower than the barrier height. CP employed quantum models to calculate tunnelling probabilities, which is crucial for determining the physical limits of miniaturisation and preventing current leakages that lead to power losses and calculation errors (Khodayari *et al.*, 2026).

Quantum computing represents the most ambitious application of QM, utilising qubits that operate through superposition and quantum entanglement. Unlike classical bits, these quantum phenomena allow for an exponential increase in computational power, enabling the processing of vast numbers of states in parallel (Oukaira, 2025). This paves the way for solving complex problems, including molecular modelling for new materials and the rapid factorisation of large numbers using Shor's algorithm. Closely related to this is the phenomenon of superconductivity, where zero electrical resistance occurs due to the formation of Cooper pairs of electrons. Superconducting circuits containing Josephson junctions are currently a dominant physical principle for creating high-coherence qubits (Huang *et al.*, 2020). Beyond quantum computers, superconductivity offers a path toward energy-efficient classical electronics. Technologies such as Rapid Single Flux Quantum (RSFQ) could enable the creation of ultra-fast processors with minimal thermal losses due to the absence of electrical resistance (Bairamkulov & De Micheli, 2024). Furthermore, quantum metrology utilises superconducting sensors, such as SQUID magnetometers, for ultra-sensitive magnetic field measurements in medical diagnostics and high-precision electronic component verification.

QM also provides the basis for absolutely secure communication through quantum cryptography, specifically Quantum Key Distribution (QKD). Unlike classical methods that rely on mathematical complexity, QKD relies on the fundamental laws of physics. Because any attempt to measure a photon's state inevitably alters it, eavesdropping is immediately detected, making key interception physically impossible (Lütkenhaus, 2019). Finally, Ab Initio modelling methods, particularly DFT, allow for the numerical prediction of physicochemical properties at the atomic level. This fundamental approach accelerates innovation across the IT industry by enabling the discovery of new SC and thermal interface materials with enhanced properties (Kleger & Meunier, 2023). Atomic and nuclear physics study the structure of the atom and its nucleus, as well as processes related to radioactive decay, nuclear reactions, and the interaction of radiation with matter. Although their role in the IT sphere may not be immediately obvious, these fields are essential for ensuring the longevity, reliability, and security of electronic systems, as well as for powering high-performance or autonomous computing complexes.

A primary concern addressed by nuclear physics is the radiation hardness of electronics. High-energy cosmic rays, such as neutrons and muons, interact with the silicon structure of microchips, causing local bursts of ionising radiation. These interactions can lead to Single Event Upsets (SEU), where a single bit state is erroneously switched ($0 \rightarrow 1$ or vice versa). Atomic and nuclear physics are utilised to model these interactions, enabling engineers to develop radiation-hardened microcircuits. This is critically important for aerospace technology, including satellites and Mars rovers, as well as for medical radiation therapy equipment and data centres located at high altitudes (de Aguiar *et al.*, 2025). Furthermore, nuclear physics plays a significant role in the energy sector as it pertains to IT infrastructure. Given that large-scale data centres consume gigawatts of electricity, there is a growing trend toward integrating small modular reactors (SMRs) or utilising nuclear power plants to ensure a stable and sustainable power supply (Vanatta *et al.*, 2024). For autonomous electronics in deep space or long-term missions where solar energy is unavailable, radioisotope thermoelectric generators (RTGs) are employed. The operating principle of RTGs is based on radioactive decay, providing a reliable source of electricity for onboard computers in environments where other power sources would fail.

Additionally, nuclear magnetic resonance (NMR) is applied within the IT industry for more than just medical imaging. While frequently associated with MRI, NMR is used for the non-destructive analysis of the chemical composition and structure of SC materials. This application was vital for quality control in microchip manufacturing, which allowed for high-precision verification of component integrity at the atomic level (Kehayias *et al.*, 2017). Interdisciplinary interconnection. The modern IT industry functions not thanks to individual branches of physics, but due to their complex interdisciplinary connection. No complex component (from processor to screen) can be designed using only one theory. Physics of the micro-world (QM, atomic physics) sets the fundamental limits for materials, while classical physics (classical mechanics, electro- and thermodynamics, optics) provides the engineering solutions for their realisation and stable operation in the macro-world.

One of the clearest examples is optoelectronics and displays, where the laws of QM, optics, and molecular physics operate simultaneously. The operation of quantum dots, used in modern QLED screens, is entirely based on QM (the quantum confinement effect, which determines the colour). However, for the correct display of the image, engineers apply optics (reflection and transmission of light) and thermodynamics (managing the thermal regime of the display, which affects longevity and colour). A similar situation is observed with liquid crystals, where electric fields (electrodynamics) control the orientation of molecules (molecular physics), and the result of their work – the reflection of light – is described exclusively by optics. Another example is the reliability and energy efficiency of microcircuits. Here, QM describes the electrical behavior of the transistor, allowing electrons to overcome tunneling barriers. However, the heat generated during the passage of such electrons is described by the laws of thermodynamics. Such a phenomenon must be taken into account by computer engineers to prevent the destruction of the material, whose properties are determined by molecular physics and quantum chemistry (Ab Initio modeling). Moreover, complex cooling systems (heat pipes), whose operation is a direct application of molecular physics phenomena (evaporation and condensation), are used to dissipate this heat.

Robotics and autonomous systems demonstrate a direct synthesis of classical physics. Mechanics is fundamental for calculating the kinematics and dynamics of the robot's motion (forces, inertia, trajectory). But for the robot to "see" the world and make decisions, optics (cameras, LiDAR) and electrodynamics (wireless communication, electric motor control) are needed. For example, an autonomous UAV uses a GPS system (electrodynamics + relativistic mechanics), inertial MEMS sensors (classical mechanics + electrostatics), and its stability in the air is controlled, in particular, by modeling the influence of wind (classical mechanics). The following Figure 2 illustrates a typical cyber-physical system infrastructure, demonstrating the close interconnection between physical processes and the software layer, where real-time sensor data informs the control logic for hardware components.

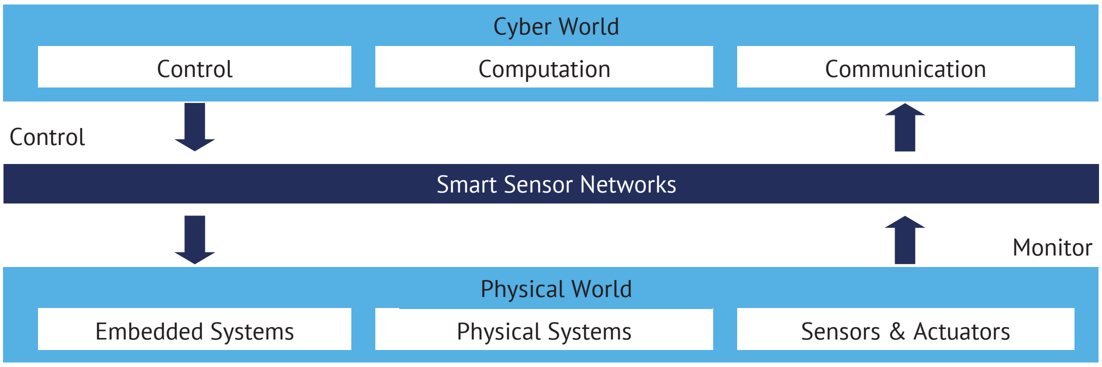

Figure 2. Cyber-physical system infrastructure

Source: compiled by the author

Thus, all IT fields, without exception, exist exclusively at the intersection of these fundamental scientific disciplines, making CP the foundation of all technological innovations. The comprehensive analysis of physical laws within the architecture of ICS reveals a profound shift from traditional hardware engineering towards an integrated computational-physical approach. The results obtained in this study underscore that the evolution of the IT industry is no longer limited by software complexity but by the fundamental physical boundaries of materials, energy, and subatomic interactions. This perspective suggests that CP has moved from being a supplementary tool to becoming the central governing framework for the future of IT. The synthesis of mechanical principles, as explored through the dynamics of high-speed components and MEMS sensors, demonstrates that classical physics remains indispensable even in a digital-first era. The work of M.A. Gharaibeh & B.M.Y. Gharaibeh (2023) regarding vibrational resistance and G.S. Chen *et al.* (2025) concerning HDD read/write head dynamics highlighted a critical point of discussion: as components shrink and speeds increase, mechanical precision becomes a bottleneck for data integrity. The necessity of modelling these systems using the FEM proved that the mechanical reliability of a system is as vital as its algorithmic efficiency. This alignment between macro-scale structural stability and micro-scale operational precision is a recurring theme throughout the study.

In the field of molecular physics and thermodynamics, the results indicate a fundamental shift from empirical manufacturing to predictive modelling. The analysis of planar technology and dopant diffusion processes, supported by the findings of I. Martin-Bragado *et al*. (2006), demonstrated that adhering to Moore's Law is primarily a thermodynamic challenge. The ability to numerically simulate atomic motion and temperature field distribution ensures a level of precision unattainable by physical experimentation alone. Furthermore, the implementation of advanced cooling solutions, as explored by I. Tari & F.S. Yalcin (2010) and X.-K. Chen *et al*. (2022), confirmed that heat dissipation efficiency and the stabilisation of thermal regimes are currently the principal limiting factors for the advancement of high-performance computing systems.

The transition from thermal constraints to electromagnetic ones is seamless, as seen in the modelling of signal and power integrity. The work of H. Jin *et al*. (2004) remains a cornerstone in understanding how electrical signals behave as electromagnetic waves at gigahertz frequencies. This study's analysis of signal reflection and dispersion confirmed that electricity and magnetism provide the fundamental language of ICS. The discussion of data storage, from DRAM to magnetic HDDs as analysed by Z. Ma (2025), further reinforces the idea that information is, at its core, a physical state – whether it be a trapped charge or a magnetic orientation. The importance of electromagnetic compatibility and shielding, supported by M.A. Morales *et al*. (2023), demonstrated that the isolation of electronic components from external interference is a prerequisite for the reliability of all modern mobile and cyber-physical systems. Furthermore, the results regarding optics and wireless communication highlight the dual nature of light as both a manufacturing tool and a data carrier. The critical boundary represented by the diffraction limit in optical lithography, discussed by V. Bakshi *et al*. (2017), serves as a bridge between classical wave optics and the quantum-scale manufacturing of the future. The application of geometric optics in computer vision and LiDAR technologies, as explored by J. Zhou (2022) and J.-K. Song & S.-T. Wu (2024), demonstrated that the perception of the physical world by autonomous systems is entirely dependent on the accurate modelling of light propagation. This confirms that optics is the primary interface between the digital processor and the physical environment.

The most significant technological shift is observed in the application of QM. The findings regarding quantum tunnelling and the physical limits of miniaturisation, supported by B. Cheng *et al*. (1999) and Z. Khodayari *et al*. (2026), prove that the field has reached a stage where classical logic is insufficient to describe hardware behavior. The analysis of quantum computing and superconductivity (Bairamkulov & De Micheli, 2024; Huang *et al*., 2020; Oukaira, 2025) defineed the strategic directions for the long-term development of ICS. Furthermore, the reliability of global security based on quantum cryptography, as described by N. Lütkenhaus (2019), demonstrated that the fundamental laws of physics are now the defining basis for ensuring information security during the transition to post-quantum standards. Finally, the role of atomic and nuclear physics in ensuring radiation hardness and providing autonomous power through RTGs (Vanatta *et al*., 2024; de Aguiar *et al*., 2025) highlights the extreme environments in which modern ICS must operate. The use of NMR for quality control (Kehayias *et al*., 2017) and the relativistic corrections required for GNSS systems (Ayso & Kahveci, 2025) serve as reminders that the IT industry must account for the structure of the atom and the curvature of spacetime to maintain modern standards of accuracy.

In conclusion, this article provides a unique synthesis of physical laws across the entire spectrum – from classical and relativistic mechanics to thermodynamics, electromagnetism, and quantum physics – demonstrating their inextricable link to the architecture of modern ICS. Unlike specialised studies that focus on isolated hardware components, this work offers a holistic interdisciplinary framework that identifies physics as the primary driver of IT innovation. The originality of this research lies in its systematic approach to bridging the gap between fundamental scientific theories and practical engineering challenges, such as the thermal wall and quantum tunnelling. By unifying these diverse branches of physics into a single conceptual model, this study establishes a new perspective on the evolution of IT, proving that the future of digital systems is fundamentally governed by the transition to a physics-aware computational paradigm.

CONCLUSIONS

The conducted research, aimed at analysing the interconnection of fundamental physical laws with the hardware and software architecture of ICS and defining directions for their future development, allowed for the formation of a comprehensive vision of the physical foundations of the IT industry. It was established that physical laws are an integral part and the basis for the functioning of ICS. Classical mechanics and electrodynamics underpin robotics, inertial MEMS systems, and LiDAR sensors necessary for autonomous vehicles and aerospace applications. The reliability, longevity, and resistance of such systems to vibrations are determined by mechanical fatigue models. Thermodynamics and molecular physics are key to the effective management of the thermal regime and solving heat dissipation problems in modern technology, emphasising the importance of CFD analysis and liquid immersion cooling. Thermal conductivity of nanostructures (e.g., PCF-graphene) is becoming critical for passive heat dissipation. Optics and electrodynamics ensure the functioning of high-speed data transmission channels and are also the basis for manufacturing technologies. Specifically, EUV remains key to forming nanometer-level microchips. QM, particularly the phenomenon of tunneling, directly defines the physical limits of further transistor miniaturisation, requiring a transition to new materials (e.g., 2D Janus LiMSSe) and architectures to circumvent these limitations. Atomic and nuclear physics play an important role in ensuring the radiation hardness of electronics, which is critically important for space-based, highly autonomous systems, and are also being considered as a potential power source for industrial and autonomous SMART complexes.

Further research should be focused on critical areas that will determine the evolution of ICS, including the development of reliable and scalable superconducting quantum qubits and the investigation of quantum protocols (e.g., QKD) for secure data transmission. Computational modeling (based on DFT and molecular dynamics methods) is also key for designing new SC materials that will allow circumventing the quantum limits of silicon structure miniaturisation. An important prospect is the integration of physically accurate real-time simulation models (based on N-body dynamics and hydrodynamic models) for extended reality (XR), which will ensure a new level of interaction realism.

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Фізичні аспекти ІТ-індустрії: від програмних архітектур до кіберфізичних систем

Тарас Ляшук

Кандидат фізико-математичних наук, старший викладач
Рівненський державний гуманітарний університет
33028, вул. Степана Бандери, 12, м. Рівне, Україна
https://orcid.org/0000-0002-2242-7537

Анотація. Функціонування сучасних обчислювальних систем базується на складному взаємозв'язку апаратного забезпечення та прикладних фізичних явищ. Актуальність дослідження визначається фундаментальною залежністю технологічних інновацій в ІТ-індустрії від законів фізики, які водночас визначають як межі (наприклад, квантове тунелювання в нанометрових транзисторах), так і нові можливості (наприклад, квантова суперпозиція у кубітах). Метою роботи було проаналізувати взаємозв'язок фундаментальних фізичних законів з апаратно-програмною архітектурою обчислювальних систем та визначати напрямки майбутнього розвитку. Методологія дослідження базувалася на системному підході, що включав контент-аналіз високоякісних наукових даних, структурно-функціональний аналіз фізичних кластерів та теоретичний синтез міждисциплінарних зв'язків, підкріплених логіко-графічним моделюванням. Основні результати дослідження виявили, що квантова механіка і термодинаміка задають фізичні межі для мініатюризації транзисторів та керують тепловим режимом мікросхем, а оптика є основою для високошвидкісної передачі даних і літографії мікрочипів. Класична механіка та електродинаміка забезпечують функціонування кіберфізичних систем, включаючи автоматизовані систем керування, роботизовані комплекси та інфраструктуру бездротового зв'язку. Проаналізовано, що молекулярна фізика та моделювання нанорозмірних структур відіграють вирішальну роль у проєктуванні нових напівпровідникових матеріалів і прогнозуванні довговічності компонентів на основі відповідних комп'ютерно-фізичних моделей. Показано, що ядерна та атомна фізика відіграють ключову роль у забезпеченні радіаційної стійкості електроніки і розглядаються як потенційне джерело живлення для високоавтономних обчислювальних комплексів. Особлива увага приділена перспективним напрямам, зокрема надпровідності, квантовим обчисленням та квантовій криптографії. Практична цінність роботи полягає у формуванні комплексного погляду на фізичні основи обчислювальних систем, що є критично важливим для комп'ютерних та програмних інженерів, науковців при розробці нових матеріалів, проєктуванні високопродуктивних і енергоефективних мікросхем, а також для створення надійних автономних та квантових обчислювальних систем

Ключові слова: комп'ютерна фізика; нанотехнології; комп'ютерне моделювання; планарна технологія; квантові обчислення; енергоефективність; цілісність сигналу