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Emerging Trends in Computer Hardware and Software Technologies: Challenges and Opportunities

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Abstract

Artificial Intelligence (AI), Quantum Computing, Neuromorphic Computing, and Edge Computing are transforming computer computational paradigms in a fast-changing manner. This paper explores recent developments in these areas, and discusses the relationship between the co-design of software and hardware innovations. Some of the major problems are energy usage, scaling limitations of the von Neumann architecture, supply chain issues, and the spectre of quantum computers destroying classical cryptography. Opportunities arise from specialized accelerators, brain-inspired computing, hybrid quantum-classical systems, and sustainable design practices. This research work presents a comprehensive overview of the hardware–software co-design, post-quantum cryptography, and energy-efficient computing techniques in the literature, published between 2023 and 2025, through a systematic literature review and industry analysis. The analysis identifies areas of research opportunities such as scalable neuromorphic systems, standardized software ecosystems for new hardware, and resilient supply chains. The paper suggests that the potential of next-generation computing can be realized through hardware–software integration and interdisciplinary cooperation, which is needed to meet sustainability and security demands.

Keywords: *emerging technologies, computer hardware, software co-design, quantum computing, neuromorphic computing, artificial intelligence accelerators, edge computing, post-quantum cryptography, energy-efficient computing.*

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Introduction

Computing is in the midst of a radical change in its scaling laws, as they are reaching their physical and economic end-of-life. The era of Moore's Law, which has been the foundation of semiconductors for decades, is coming to an end, as Moore's Law is being replaced by more diverse architectures, purpose-built accelerators, and even novel computational paradigms (Deloitte, 2024). At the same time, software is moving from a monolithic application into the realms of agentic AI, distributed edge intelligence, and tightly integrated hardware–software co-design. These are not just "small" changes, but a paradigm shift in the way computation is thought of, built and used.

AI has proven to be the one force influencing hardware innovation. Large language models and generative AI have driven an unprecedented demand for the use of high performance computing resources, with a primary focus on graphics processing units (GPUs), neural processing units (NPUs) and custom application specific integrated circuits (ASICs). Analysts estimate that the AI chip market will grow significantly over the next few years into the next decade (TechInsights, 2025; Deloitte, 2024). Concurrently, quantum computing is moving from demonstration to early practical applications and certain areas of work are expected to see orders of magnitude improvements in energy efficiency through neuromorphic systems (Davies et al., 2024).

These advances offer significant possibilities as well as significant challenges. AI training and inference at scale poses significant sustainability issues. With the imminent ability of quantum computers to crack popular public-key cryptosystems, a timely shift to post-quantum cryptography is essential. The challenges of supply chain concentration, geopolitical tensions and talent shortage further complicate the way forward. This paper aims to present a structured analysis of these trends, challenges and opportunities that has been informed by recent scholarly and industry literature.

Literature Review

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In the field of Artificial Intelligence, hardware acceleration allows for more efficient processing and speeds up the speed of operations.

As AI workloads take the lead, semiconductors have seen a shift in investment focus to specialized accelerators. While GPUs continue to play a key role in training large models, the use of neural processing units (NPUs) in client devices provides a way to deliver on-device inference with significantly reduced latency and power usage (Deloitte, 2024; TechInsights, 2025). In addition to this, hyperscale cloud providers are developing their own silicon chips, which are eroding the competitive advantage of the traditional GPU suppliers.Furthermore, hyperscale cloud providers are developing their own silicon chips, eating into the GPUs manufacturers' moat. Beyond process-node improvements, advanced packaging is essential enablers to performance scaling, such as chiplet architectures and high-bandwidth memory (HBM) chips (Plunkett Research, 2025). Edge AI is an alternative path. By 2025, over 50% of data will be created at the edge, necessitating efficient edge devices with local computing power to run compressed models, according to Deloitte (2024). This move means that autonomous systems, industrial IoT and mobile applications can rely on real-time decision-making without having to depend on centralized data centers, enhancing privacy at the same time.

Quantum Computing

The march of quantum computing towards reality. The advancement of quantum computing is progressing toward several platforms, including superconducting qubits, trapped-ion qubits, photonic qubits, as well as emerging topological qubits (Gao & Adnan, 2025). Fault-tolerant universal quantum computers are still a ways off, but noisy intermediate-scale quantum (NISQ) devices are already being used for optimization, simulation and some machine-learning applications. One immediate consequence is the cryptographic threat: With the arrival of large-scale quantum computing, RSA and elliptic-curve cryptography are projected to be broken, and therefore, post-quantum cryptographic algorithms are being developed and standardized (Deloitte, 2024; Gartner, 2024).

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Neuromorphic and Brain-Inspired Computing

The idea of neuromorphic computing is to overcome the inefficiency of energy consumption that arises from von Neumann architectures by placing memory and computation close to each other in a manner that follows principles of biological neural systems. At a large scale, spiking neural networks have been shown to be viable with platforms like Intel's Loihi, SpiNNaker and BrainScaleS (Davies et al., 2024). The last years' surveys highlight that hardware–software co-design and more established software ecosystems must be implemented to take neuromorphic systems beyond specialized research applications (Shrestha et al., 2024). Another advantage of photonic neuromorphic approaches is the ultra-high bandwidth and ultra-low energy consumption of linear operations, which are at the core of neural networks (Shastri et al., 2024).

Tackling the challenges of software development.

Growth in software continues to be in parallel with hardware advances. The Agentic AI systems expected to be able to make and execute plans and take actions autonomously will impact an increasing percentage of routine decisions (Gartner, 2024). The efficient deployment of models compressed, quantized, and specialized in small language models is making AI accessible to resource-limited devices. Importantly, the literature is starting to acknowledge that co-design is necessary for optimal performance: algorithms and models should be developed taking into account the constraints on the hardware, and hardware architectures should be informed by the properties of the work loads to be executed. (Gao & Adnan, 2025)

Research Gap

While some major strides have been made, there are still some key gaps. First, the software ecosystems for neuromorphic and quantum hardware are not yet as mature as the hardware, which restricts broader adoption (Davies et al., 2024). Second, there is a lack of comprehensive approaches that consider the overall cost of ownership of new computing paradigms, such as energy cost, carbon footprint and supply-chain risk. Third, there have been no widely adopted

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standards for post-quantum cryptography, and there are fewer resources than usual available to help with migration strategies for large-scale legacy systems. Fourth, there is a limited number of cross-cutting methodologies that cover the three types of hardware—AI accelerators, neuromorphic chips, and quantum processors—in the literature of hardware–software co-design.Fourthly, there are few cross-cutting methodologies in the literature that cover the three types of hardware: AI accelerators, neuromorphic chips and quantum processors. Lastly, real-life deployments of these technologies have not been extensively quantified in terms of societal or economic impacts, compared to technical performance metrics.

Objectives

The aim of this paper is to achieve the following:

1. Delineate and combine the key trends that are currently being observed in computer hardware and software technologies from recent scholarly and industry sources.
2. To discuss the main technical, economical and security issues that are related to these trends.
3. To analyse the potential for innovation in the area of co-design of hardware and software, special purpose accelerators, and alternative computing paradigms.

To identify the missing research and suggest future areas of study that can speed up responsible and sustainable adoption.

Methodology

For this study, a systematic literature review approach is used. The articles, conference proceedings and authoritative industry reports published between 2023 and 2025 were selected using IEEE Xplore, ACM Digital Library, Nature journals, ScienceDirect and industry reports from Deloitte, Gartner, TechInsights, World Economic Forum. Sources were selected based on the following criteria: They must discuss hardware or software innovations and explain the technical challenges, performance characteristics, or implications of the innovations.

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Priority was placed on article reviews, empirical research and high-impact analyses. ALIST has been mapped into 4 thematic clusters: AI hardware and acceleration, quantum computing, neuromorphic systems, and software co-design and security. No primary experimental data were gathered, but the contribution was in the structured synthesis and identification of cross-cutting insights and gaps.

Results

By synthesizing recent literature, we obtain a few consistent findings. Firstly, AI is still taking the front seat in the hardware roadmap. There is increasing demand for accelerators, which is pushing both process-node shrinking and new architecture, such as chiplet designs and advanced package. High-performance NPUs enabled personal computers are expected to become a significant percentage of personal computers shipped and will likely lead to a personal computer refresh cycle (TechInsights, 2025). Secondly, the development of quantum computing is relatively slow and uneven for the platforms, and the next most likely application is not a general computational power gain, but instead a cryptographic shift. Third, although there are powerful energy-efficiency benefits of spiking and event-driven computing with neuromorphic systems, these systems are held back by limited standardization and immature software stacks (Davies et al., 2024). Fourth, software trends focus on agentic systems, model efficiency techniques and the need to be hardware aware when designing algorithms. Fifth, sustainability and supply-chain resilience are no longer tick-box items for industry and policy, but an integral part of industry and policy strategy.

Discussion

Challenges

One of the main challenges is energy and environmental sustainability. Power consumption is very high during frontier AI training, and energy limits in data centres are already hindering the rollout of frontier AI in certain parts of the world (McKinsey, 2025). Neuromorphic and specialized accelerators also provide opportunities for increased efficiency, but will only be realized if workload is

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mapped onto them, which is a continuous problem in research and engineering. The error rates and overhead of quantum error correction are limiting scalability of quantum systems. Concentration in the supply chain in the manufacture of advanced semiconductors adds geopolitical and economic risks. Last but not least, to move to post-quantum cryptography will take a great deal of coordination among software layers, standards organizations, and organizational security practices, which is technically challenging and organizationally challenging.

Opportunities

There are also significant opportunities along with these challenges. The use of hardware–software co-design can generate performance and efficiency improvements which are not possible using sequential optimization. Edge AI brings the power of intelligent solutions to environments that demand low latency and high trust, such as privacy-sensitive areas. Even without fault tolerance, hybrid quantum-classical algorithms could provide benefit for certain high-value problems. Neuromorphic platforms are uniquely suited for continuous sensing, adaptive control and low power edge intelligence. More generally, AI, advanced materials, photonics, and quantum technologies enable combinatorial innovations, which none of these technologies alone can offer (World Economic Forum, 2025).

Implications for Research and Practice.

Portable software abstraction and programming models across heterogeneous hardware should be the focus of researchers. Energy efficiency, crypto-versatility and diversity of the supply chain are not second-order issues, but first-order design constraints for practitioners and policy makers. Investment in talent and development from the hardware architecture, algorithm design and systems software will be crucial to realize the potential identified herein.

Conclusion

New developments in computer hardware and software technologies are challenging the computational capabilities of the computer. Overall, the combination of these technologies and innovations—AI accelerators, quantum

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processors, neuromorphic systems and complex software co-design methodologies—suggests a more heterogeneous, efficient and intelligent computing environment. This potential can only be unlocked by purposeful focus on energy sustainability, cryptographic resilience, software maturity, and supply-chain robustness. The research gaps that were identified, namely the lack of scalable software ecosystems, cross-paradigm co-design methodologies and holistic impact assessment, are priority research areas. It will take time for progress to be made if hardware designers, algorithm developers, systems researchers, and domain experts work together. The computing community can take advantage of these new technologies to provide significant scientific, economic and societal benefits by addressing both the technology challenges and the technology systemic issues.

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