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Chapter 12: Forecasting the future: From quantum chips to neuromorphic engineering and bio-integrated processors

12.1 Introduction to Advanced Computing Technologies

Computing is at the forefront of advances in human civilization and technology. Alongside communication, it is a critical technology that often drives improvements in many other scientific fields. Over the last 60 years, computing has achieved unprecedented advances attributed to scaling laws predicted by Moore’s law, whereby the number of components on a chip doubles every two years, and Dennard’s voltage scaling, whereby the voltage of components is also halved. However, continuous similar advances are no longer necessarily guaranteed, leading to the potential emergence of the so-called ‘Beyond Moore’s Law’ era. Even while traditional transistor scaling is ending, the demand for computing continues to grow in all sectors of the economy by almost orders of magnitude. The end of traditional scaling is expected to result in a computing crunch due to an energy crisis, necessitating the exploration of renewable sources of energy and computers that consume far less energy. Among many possible alternative computing architectures, neuromorphic computing based on brain-inspired computing is one of the most promising (Feng et al., 2018; Himelstein, 2022; Schell, 2024).

New unconventional computing paradigms have emerged to contend with the traditional computing challenges in the five challenge arenas. In the energy-cost arena, they exploit new multiple physical phenomena such as memristive devices, ferromagnetic nanomagnets and spintronic logic. In the computational-speed arena, they leverage the unique temporal dynamics of a wide variety of oscillators based on magnetic, photonic, ferro electromagnetic and nanomaterial technologies. In the footprint arena, they take advantage of in-memory computing, flexible and low-footprint nanomaterials and 3D integration. In the cyber-resilience arena, they leverage a plethora of nanomaterial-based technologies with built-in fault-tolerance mechanisms. In the data arena, they utilize a new generational speedup of the data deluge with hybrid mixed-dimensional nano-material systems with advanced consensus-led strategies. They provide a roadmap towards the realization of a novel, energy-efficient, ultra-fast, compact, secure, resilient, and capable computing technology for the Big Data Age that will complement today's dominant computing technology based on CMOS transistors. Just as nanotechnology broadly focused on experimental materials and devices ushered in the 21st century, unconventional computing galvanized by nanotechnology will be a critical driver of advances in the 21st century and beyond (Nvidia, 2025a; Nvidia, 2025b).

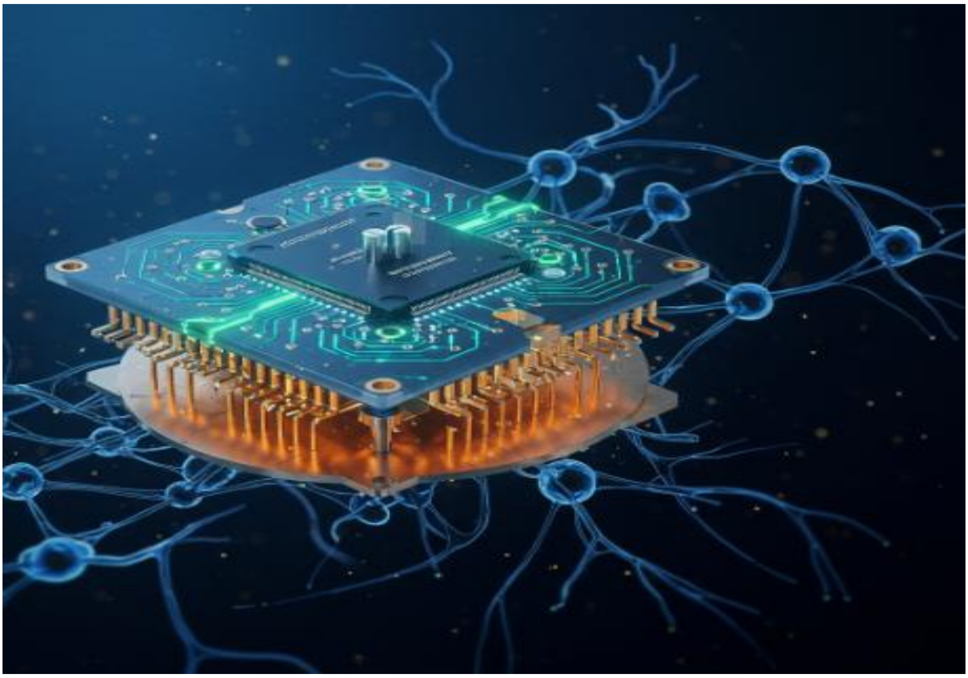

Fig 12.1: Quantum Chips to Neuromorphic Engineering.

12.1.1. Background And Significance

Information technology is expected to play a major role in determining the future direction of biotechnology. Current genetically-engineered DNA chips, protein chips, and micro-array systems for studying networks of molecular interactions in bioinformatics are mostly passive. They allow for monitoring of concentration variations upon perturbation of a biological system. This is akin to the arrangement of channels in a classic neuro-computer. Information on the dynamics of the system can be extracted only after the fact, and cannot allow for perturbations of a biological system based on the collected information. This is also the case for transistor-based logic chips. The integration of increasingly smaller components has led to a diminishing presentation of asymmetries in IR spectra, an increasingly larger number of metal connections, and, ultimately, to systems that are nothing more than a layer of metal connections. The answer to the question on which process had led to the full complement of the micro-tubular machinery in a neuron may not be found out by these types of continuous variable technology. For this reason, it would appear that present generation biotechnology and information technology need a new direction.

The merger of nanotechnology, biotechnology, and quantum physics may allow for the formulation of the basic principles of a radically different form of information technology. The foundation of the new technology must not exclude the vast spectrum of plurality of organization, nor optimize a single type of computation or representation. Rather, the new technology should lend itself to an open-ended development that allows for a suitably rich interaction between different types of agents. The characterization of the sources of novelty as expressed in biological and social evolution provide a useful starting point. The basic principles of any realizable system of the technology to be elaborated are: (i) At all stages of natural evolution physical systems are subject to basic physical processes. These processes select from a wide set of equally possible initially realizable states a complementary pair of physical geometries and continuous variables. The asymmetries thus produced are used as a source of continuous variable information, while acceptors of this information simultaneously operate on its flow by selecting on the basis of their own idiosyncrasies the probabilities of the selected complementary set of physical processes and are changed by so doing.

12.2. Quantum Computing: Principles and Applications

Quantum computing has gone from strength to strength in the past couple of decades. Indeed, it is commonly accepted now that, next to neuromorphic computing, quantum computing is the best-known alternative to conventional, transistor-based computing. Perhaps, especially because of the competition between rival tech giants, companies like IBM, Google, Intel, and others make it inevitable that the newest developments within quantum computing receive significant media attention with promises of revolutionary speed-ups in some computational classes and threats that existing cryptography could be broken. The technology to build universal quantum computers has not quite arrived, however. Recent noise-scaling and fidelity-improvement techniques have indeed pushed computation results to error rates that are orders of magnitude more favorable for some sparse-matrix-matrix-multiplications, consequently increasing interest from the computational chemistry community. However, high-fidelity gates in larger devices remain out of reach in practical applications. Yet even when these first modest applications are securely demonstrated, it is unlikely that they will alleviate the need for the widespread development of alternative schemes of computation.

There are a couple of reasons for this need. First, interest in quantum computation is not limited to numerical questions. All of quantum mechanics — throughout its derivation from more long-standing interpretations of von Neumann — has a computational angle by permutation of vector spaces. Thus, in a wider sense, all of quantum mechanics represents an immense defeat for classical theories of all kinds, complicated or not, and the unprecedented parallelism related to it is, arguably, the most significant development in the last century of physics. What should be expected of quantum computation within the realms of quantum mechanics is far from clear and anything but modest. For future quantum computational paradigms to be fully realized, this original interest in quantum computing based on something more foundational than hardware would likely need to gain momentum as the number of qubit and compute cycles required for an initial universal quantum computer scales unfavorably.

Second, preliminary estimates of speed-ups by quantum computing currently rely on assumptions of significantly higher coherence times than those typically expected in projected devices. Further, they involve very sizable amounts of number-crunching that seem feasible only to classical computation, raising fundamental questions on variances amongst cosmological constants far beyond any observed value. Indeed, even assuming this possibility, it would seem counterintuitive that such a remarkable need for quantum computation would not have been anticipated and catalyzed before. Similar consideration applies for the eradication of this need by the computational discoveries themselves. The models on which preliminary estimates of speed-ups and artefacts of classical computation in quantum domains rely become almost intractable themselves as conditions deviate from ideal symmetry assumptions.

12.2.1. Fundamentals of Quantum Mechanics

The vast development of technology enabled by the progress in material science, nanotechnology, electronics, optoelectronics, etc. is believed to experience a technological road bump, broadly defining a virtuous circle of discovery => invention => adoption => improvement that sustains the rapid technological progress. Equivalently, one can view this as a wave of technological progress that continues until it reaches a valley caused by a workload voice or some other issues necessitating a different technology to improve the signal-to-noise ratio, response time, functionality, etc.

Quantum computing (QC) is believed to be a potential candidate to alleviate computational bottlenecks imposed by classical computing (CC) for problem types based on quantum phenomena such as quantum systems simulation, non-polynomial complete problems, data security, etc. On the other hand, some believe that quantum-inspired algorithms executed on a mapped CC might achieve practical speedup. Nonetheless, even amongst the believers, not all are pessimistic, since there are many paths toward QC based on different qubit physic approaches such as superconductor qubit, trapped-ion, neutral atoms, photonic qubit, etc. These recently developed techniques are so unique and have algorithmically nondirajuable variation that the finite testing on specific tasks such as number factoring or quantum state sampling could lead one approach a few hundred years of gain - hardly dismissible.

Nonetheless, it is important to leverage existing devices and work toward synergistically combining classical and quantum devices such as building locally high-performance devices within the already-existing versions of devices and embedding them on chips. Indeed, guillotine waveguides for low-loss waveguide couplings between nanosystems and electromechanical waveguide combarrays demonstrate the ability to be integrated alongside photonic circuits. Helios spin qubits are extremely tunable and a large number of designs and models are optimized at the device and circuit netlist levels. Yet, many essential tasks remain to be met on the architectures and proof tests.

The competition of different devices' papers on intelligent computing chips draws attention to broad niches - beyond understanding classical computer systems - yet little integration is demonstrated. To this end, a bio-integrated ultra-low-energy 2D all-solid-state tomographic imaging brain-state monitoring and nanomaterial-based fluorescence-active chemical components synthesis system on a bio-interface chip was fabricated.

12.2.2. Quantum Algorithms and Their Impact

Among the quantum algorithms found up to now, the most cited is Shor's algorithm that uses quantum superposition to factor large integers into primes in polynomial time, while the best classical algorithms need time exponential in the number of digits of the number. This algorithm would render today's famous cryptographic systems, based on the difficulty of factoring large numbers, useless. Other well-known quantum algorithms exploit similar ideas: quantum algorithms for simulation of quantum systems with the next best algorithm considered to be Grover's search, which uses quantum interference instead of superposition for searching an N-# database and finds the answer in $O(\sqrt{N})$ instead of $O(N)$ classically. The impact of quantum computing has been studied as a whole and by subjects or sectors. If successful, quantum computing will be a general purpose technology (GPT) that will fundamentally alter some sectors and create new products, services, and, thus, companies. Research is focused on algorithms and applications for quantum computers that do not exist yet and are based on a technology that might never be viable. Still, it is reasonable to assume that quantum computers will exist at some point and that the initial assumptions will be mostly correct. At the core of the forecast is the analysis of the philosophies and methodologies that have been used in the past to analyze the impact of emerging general purpose technologies, with an emphasis on the impact of computers and of the Internet as a general purpose technology.

12.2.3. Challenges in Quantum Hardware Development

In the wake of Moore's law, quantum computing is envisaged to transcend the limitations of classical computing. Quantum chips based on superconducting and hybrid systems are being explored for their quantum advantage in real-world applications. A roadmap covering the next 5–10 years, exploring the hurdles to scale-up to larger systems, is proposed that is applicable to a range of physical realizations.

Moore's law predicted an exponential increase in transistor density that would result in a commensurate increase in logic performance. For several decades, this prediction held, resulting in an exponential increase in the economy of integrated circuits (ICs)—the engine behind the computing and information technology revolution. An accompanying decrease in the price per transistor and, therefore, improved performance on an unprecedented scale had wide-ranging impacts across many sectors: communications, information storage, transportation, health care, logistics, security, biotechnology, finance, materials, construction, education, and entertainment. However, for the last decade, skeptics have pointed out that the exponential increase in transistor density that has driven the productivity of the IC industry will soon cease. As transistors shrink towards the size of a few silicon atoms, accelerating power dissipation and leakage currents threaten even larger but improbable chips. In addition to these physical limitations, a fundamental conundrum arises: What will happen to the net performance of large computing systems when billions of transistors capable of executing a billion operations per second are packed into a unit volume? On the one hand, the collapse of Moore's law connotes the end of a robust and successful trajectory. On the other hand, this event has been anticipated and will be overcome, just as the end of horse-drawn carriages was matched by the arrival of the automobile.

12.3. Neuromorphic Engineering: Mimicking the Brain

The human brain is an incredibly well-architected biological structure made of neurons, which work in concert to convey an exquisite combination of functionality and physical design. The most conspicuous merit of the brain architecture is its efficiency in information handling, in terms of energy expended per solved task. Neuromorphic engineering (NE) is a new highly interdisciplinary branch of engineering, which aims at mimicking aspects of the functionality, dynamics and physics of the brain in artificial systems. The NEW approach uses architectures and algorithms inspired by biological systems, in contrast to the present mainstream high-performance computing based on the Von Neumann architecture. Efforts in NE are driven by the consideration that the brain is a captivating example of natural design and engineering, whose solutions are frequently incredibly efficient and optimized for a wide variety of tasks.

NE has a twofold and intertwined objective: one, a scientific goal to understand, from a computational perspective, how intelligent behavior arises from biological neural systems; second, an engineering goal to exploit the known properties of biological systems to design and implement for engineering applications efficient devices. The interesting aspect NEs try to exploit is the architecture of large scale neural systems and the associated parallelism of information handling at different time-scales and processing levels. The emergence of Large Scale Integrations (LSI) technologies permits the insertion of a number of components in two-dimensional spaces and power supplies that makes it possible to emulate hardware neural on-chip models with complex dynamics such as spiking background noise or chaotic behavior. The third, and last, aspect is related to the effort to design architectures suited for the emulation of brain-like computation, thanks to complex neuro-inspired architectures designed to reproduce specific aspects of neuron and synapses, or assemblies of them, originally proposed within neurological and biological studies.

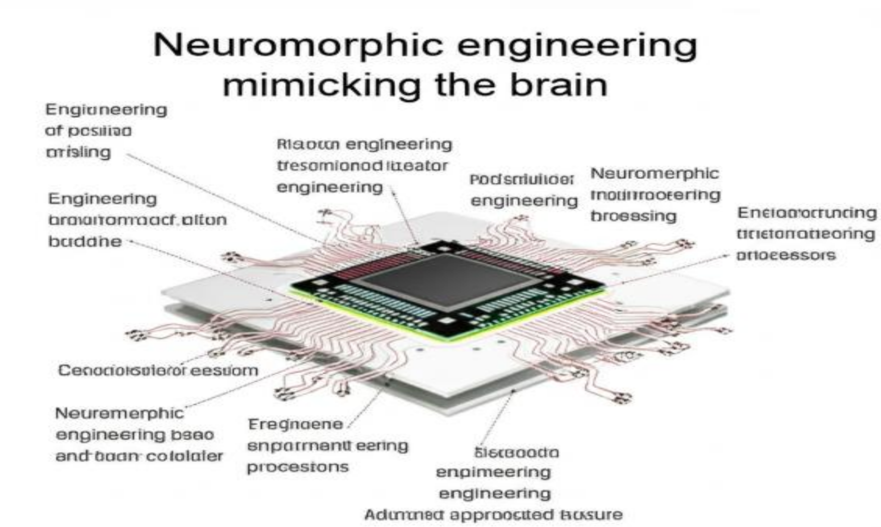

Fig 12.2: Neuromorphic engineering: mimicking the brain.

12.3.1. Overview of Neuromorphic Systems

Neuromorphic systems attempt to implement in hardware specific computational rules that are used by the biological brain via a multitude of interconnected neurons communicating using spikes. The main distinction between the neuromorphic and non-neuromorphic systems is the mechanism of communication and processing. This section provides an overview of the more advanced and interesting candidate neuromorphic systems that are currently under development across the world.

In the same way that the transistor revolutionized classical computing by allowing electronic communication and processing in the form of charge packets in integrated circuits, several breakthroughs in devices, architectures, and interconnect technologies for radiation or bio/chemical sensors are currently promising to transform neuromorphic sensing and computation. Indeed, a host of neuromorphic architectures inspired by the biological principles of information processing in the brain are being developed today to cope with the flood of data generated by pixels in high-resolution image sensors, emitters, and antennas, and with the demands of low energy and ultra-fast learning when scaling up to very large numbers of sensors.

Currently, there are several neuromorphic systems that are computationally able to implement more sophisticated integrative/sustainable knowledge extraction processes involving several steps. On-going proposed implementations and their anticipated performance in terms of accuracy, learning speed, density, and energy consumption are discussed. In particular, it is shown that they can all implement beyond real-time learning, in which the weight updates are performed on a spike-by-spike basis, as well as a type of short-term plasticity based on weight-dependent spike-timing windows, which is the mechanism believed to confer the temporal dynamics for the high ordering of the visual scene encoded in onion-like structures formed by the rat retina, LGN, and V1. Finally, it is suggested that they can be integrated in a single chip.

12.3.2. Applications in Artificial Intelligence

Emerging devices such as memristor and RRAM are promising candidates for low-power and highly parallelized inference processes. However, due to highly non-ideal behaviours of the devices, the path from edge to cloud is found to be ill-posed. Correcting for the nonidealities of the devices is therefore crucial for deploying the emerging architectures in real-world applications. This chapter discusses the challenges of real-time learning with emerging devices and some possible solutions.

Recent years have seen a surge in the R&D of low-power and highly parallelized hardware accelerators for deep learning. Several critical bottlenecks, however, are inherited from the compute-heavy nature of current algorithms and architectures. They include the heavyweight matrix multiplication and the proliferation of memory in deep learning models. In-memory computers in which computation occurs in the memory and the memory nodes are also the computing nodes are attractive candidates to address these challenges caused by the von Neumann bottleneck. A class of emerging devices, i.e. resistive switching based devices, is promising for real-time and highly parallelized inference.

The fundamental non-idealities common in non-volatile memory include read and write noise, nonlinear read/write current-voltage characteristics as well as nonuniformity of the switching threshold voltage distribution. In this context, the critical paths to be corrected to make accurate inference on neuromorphic processors with RRAM based crossbar would be discussed. Possible solutions relying on the digital controller electronics as well as the analog circuit would be introduced. Nonidealities of the emerging devices may be inferred from an auxiliary in-situ small-scaled crossbar and therefore be corrected in real-time.

12.3.3. Comparative Analysis of Neuromorphic and Traditional Computing

The brain can be viewed as a massively parallel information processing device, which exhibits great flexibility and robustness despite its inherently noisy circuits and nonideal components. Following the recent advances in various computing technologies, there has been a growing interest in building brain-inspired large-scale computing machines that match the size, energy efficiency, dynamic range, robustness to noise, and fault tolerance of biological systems. Extensive studies at multiple spatiotemporal scales have resulted in the development of exciting new computational paradigms including quantum computers, neuromorphic processors, and bio-integrated implementable systems. In addition, innovative architectural styles and algorithmic designs have been proposed to leverage these different approaches to building brain-like computing machines. A comparative review of these emerging computing paradigms is discussed in terms of their theoretical and practical merits and challenges in their synergies for building next-generation ultra-large-scale computing devices. It focuses on recent experimental advances in the four different computing approaches, fundamental ideas and breakthroughs underlying their computational principles, and comparative analysis of their strengths and weaknesses in their practical implementations, possible physical realizations, and versatility to tackle specific problems.

12.4. Bio-Integrated Processors: The Future of Computing

Bio-integrated computing systems, resembling the cyborgs of science fiction movies, combine living components with synthetic ones, potentially altering how computing is perceived. Such systems utilize signal-processing principles often overlooked, which, when implemented with CMOS technology, cannot be scaled due to high power consumption and limited integration density. Optic flow computations, ubiquitous in biological or animal solutions, have inspired an innovative high-performance CMOS chip that exploits massively parallel and asynchronous spike communication, achieving unprecedented performance at ultra-low power consumption.

Electrical signals generated by biological neurons are used rather than chemical signals in hybrid biocomputers. Such a setup permits reducing both the electrical thresholds and amounts of the ions applied for long-term potentiation/depression with bulk and individual electrodes, both with the advantage of reducing the power consumption. Biohybrid area-efficient spike detector networks producing an output event driven by the incoming spike train discriminated on the temporal features of the spikes were conceived for the integration of biological neurons on a chip and tested using an excitatory spike train from a simple hardware spike generator with active on-chip components.

These biohybrids are envisaged for future spike event-driven computing in superefficient integration and learning in a massively parallel manner. Successfully closing the spike-communication loop between biological and synthetic spiking neurons, it is demonstrated locally on the same chip, facilitating biohybrid neuromorphic computing to directly solve biologically inspired computational tasks. Continuing the improvement of the flocking biohybrid device group that robustly exhibits flocking behavior and extending the experiments with more biohybrid entities has been proposed. In parallel, the modeling approaches based on the Hidden Markov Model and Dynamic Bayesian Network have to be significantly improved, especially in the input-output formalism.

12.4.1. Definition and Importance of Bio-Integration

Bio-integration is a technology to integrate biological and artificial systems. Bio-integrated systems, that embed organic donor materials in electrical components, have meritorious biocompatibility and bioactivity with high performance for bio-application. To achieve bio-integration of field-effect transistors (FETs), organic semiconductor-based device technologies as well as screening of candidate materials with benign chemical properties are required. Organic devices show great promise in wearable and implantable bio-electronics due to their complementary properties such as high flexibility, sustainability, and biocompatibility. These organic devices can be integrated with biological systems with little or no physiologically harmful effects as compared to inorganic counterparts. This encouraging property is due to the organic materials which are readily amenable to synthetic modifications that create numerous candidate materials with benign bioactivity. A few examples of bio-integrated devices using organic semiconductors include a bio-integrated organic amplifier and bio-integrated organic phototransistors. Bio-integrated devices show promising performance for bio-signal monitoring and modulation. However, they are still insufficient for device technology maturity. In this section, a complete solution for the bio-integration of FETs would be presented. First, bio-compatible conducting polymers are developed to replace the gate dielectric of organic FETs. In-depth characterizations are performed to investigate the biocompatibility and stability of organic devices in aqueous environments. High-performance organic ion-sensitive FETs (ISFETs) are demonstrated for the first time based on bio-integrated FETs, and their great potential for bio-application is verified. The biocompatible conductive polymer as well as advanced device technology will pave the way to bio-integration of a wide range of organic devices.

12.4.2. Current Research and Developments

Several computer engineering groups have recently begun exploring ways to rethink the fundamental architectures and processes of classical computing systems using quantum constructs. Ultimately, such a project entails achieving what has no classical analogue: a quantum computational process that produces classically non-equivalent results using a collection of qubits, each transitioning under continued control by programmable Hamiltonians between energy states that are entangled in ways not possible with classical bit states. Several groups explore on-chip applications designed to offer fundamentally useful devices but built using well-understood solid-state fabrication. Exploiting coherent multi-qubit operations within solid-state devices is advantageous in terms of scalability, yield, integration density, manufacturability and interoperability with other systems. Research ranges from implementation of quantum gates and devices to benchmarking, error mitigation, and simulation of exotic physical processes. Examples include spin qubits based on electrostatically confined electrons in silicon quantum dots, as well as superconducting qubits based on Josephson junction circuits and lattice optical systems for neutral atoms. Additionally, promising results concern the integration of these platforms with high-performance photonic systems for hybrid quantum networks, as well as physically independent systems operating in parallel.

Researchers actively engage in emerging technologies, including neuromorphic devices and systems, as they explore new horizons and devices for devices fabricated using 21st century materials and processes. Generally conceived as an alternative to the von Neumann computing paradigm, the study of neuromorphic devices and systems focuses primarily on implementing physical neural processing systems using contemporary physics. The biologically inspired neuromorphic devices are presently a wide variety of device types, material systems, and geometries. These would-be biological neurons employ varistors and semiconductor heterostructures, ionic drift and electrolysis, electrically-active 2D materials and ferroelectric polymers, as well as superconductors and photonics. Global fabrication technologies employed in such studies typically include MEMS, hybrid processes, and 21st century 2D materials. Numerous groups have examined architecturally limited nonlinear devices, using only a few materials or devices, yet pursuing essentially parallel networks employing massive parallel connection of lossy, low-state, slow response devices considered biologically acceptable alternatives to CMOS processing techniques. More ambitiously, there are groups exploring architecturally unlimited systems that implement physics other than formal neural systems.

12.4.3. Ethical Considerations in Bio-Integration

The proliferation of biointegration technologies that merge artificial and biological systems raises ethical considerations across a number of domains, with implications for justice, autonomy, safety, workmanship, workplace, warfare, and freedom. While a full discussion of these issues is beyond the scope of this text, the area of biointegration pertinent to the neuroscience and neuro-technological frontier is presented here; two major areas of focus are highlighted, along with several questions to prompt deeper ethical consideration for implementation of the technologies.

Broadly, biointegration refers to technologies that are implanted or otherwise incorporated into the human body or psyche; these devices affect the biological system either directly (via mechanical inputs or organic output); or indirectly (via the transmission or invocation of chemical, electrical, or pharmacological processes); and they can be generally classified into a number of categories based on their application and function, including: neural implants, emotion bears, and neurological addition. With advances in electronic miniaturization and polymer-based biointegration materials, bio-integrated devices that are supple, safe, and reliable are now available, and examples include temperature sensors, pressure sensors, blood oxygen levels, and neural probes. Each of these examples carries a large downstream impact for the individual, individual relationships with family, friends and neighbors, larger social systems, democracy, and harmony with the Earth.

12.5. Interdisciplinary Approaches to Computing

Although current advancements focus on ways to accelerate existing binary computational architectures, there is a growing recognition of the need for intelligent systems (IS) that will inevitably require novel concepts and architectures. In the 'beyond Moore's law' era, domain-specific computing will become increasingly important as edge intelligence becomes more ubiquitous. Recently, a plethora of new unconventional computing paradigms have emerged to tackle these challenges, covering a considerable part of the computing performance and efficiency spectrum. For some of these, new scientific principles have recently been unveiled, providing the first glimpse of practical systems, be they dedicated hardware or programmable algorithms, that employ them for real-world applications.

To bring together the widest possible spectrum of nanotechnologies that can potentially be adopted for the implementation of unconventional computing — that is, new computer architectures beyond the silicon digital paradigm, while also addressing the unavoidable emergence of quantum effects — this roadmap focuses on emerging nanotechnologies and interface science. It chiefly concerns computing platforms based on hybrid approaches that intertwine devices, searching for synergetic properties that are not obtainable without an ample toolbox of technologies. The intersection of discrete and continuous variables, analog and digital, classical and quantum technologies, as well as on-chip and off-chip computations, is expected to give rise to unexplored yet fruitful research avenues, benefitting energy cost, computational speed, reduced footprint, and data processing prowess.

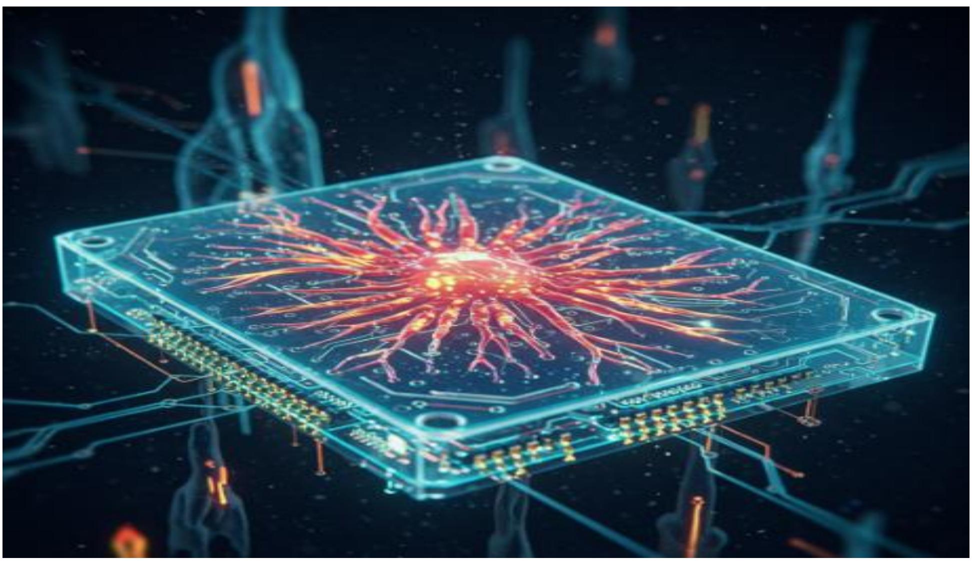

Fig : Future of Neuromorphic Engineering and Bio-Integrated Processors.

Assuredly, the canonical microelectronics scaling of classic transistor-based architectures is reaching its limits, with economies of scale diminishing rapidly. New scientific principles and paradigms will have to be embraced to make progress in computational efficiency, speed, and energy costs. By bringing together a wide spectrum of CMOS-compatible nanotechnologies for unconventional computing, the roadmap outlines an interdisciplinary research agenda that may have a decisive impact on computing in the decades to come. Through novel approaches — such as extensive relying on non-standard architectures; employing physics beyond standard energy barriers; conceiving materials and devices with no counterpart in today's standard platforms; and hybridizing them in systems-on-chip — an elevated degree of computing versatility, efficiency, and power (both in senses of per unit energy costs and shadow) is expected in the near future.

12.5.1. Collaboration Between Fields

Collaboration between fields, or cross-pollination, is generally slower compared to the improvement of one's own field in applied technologies. One way to overcome this lag is the concept of international collaboration such as hosting international workshops, conferences or competitions. These events would bring together institutions globally and provide an interdisciplinary playground for young researchers. The young researchers would be prospective future leaders who have the most extensive knowledge of the current technology. It would be especially helpful to have leaders in attending such events.

The brain is different from any existing computing architecture. Follow-up education is crucial to enable those who focus mainly on electrical engineering or physics to develop an understanding of and possibly a passion for neuroscience. This includes the brain's biochemical and neurobiology whereas existing education on brain-inspired technology would only cover superficial operation principles. Such an initiative requires many experts in neuroscience and profound knowledge of all aspects of computing and computing hardware. In addition to hosting an initial event, a continuous endeavor is required to maintain a stream of updated knowledge. Internet-based video courses could be a useful tool, although careful design is required to create engaging courses that lead to a profound understanding of concepts, not just rote memorization.

One possible long-term perspective is that such a challenge could be partially overcome through the development of generalized co-between computing hardware. This would be potentially useful to establish interactivity between the Pepsi challenge and the glass box understanding of shallow networks. However, it would be impossible to tackle the challenge with technology developed in today's von Neumann's architecture due to severe bottlenecks in speed and power. Mindism, which rests on reshaping electrical and chemical waves into discrete activities, could not only provide a new perspective for understanding the brain but also offers a new potential for the future of computing hardware and neuroscience unlike the existing technology-oriented ideas in the neuromorphic computing community. Such a breakthrough would open up many new questions, including ethical ones.

12.5.2. Case Studies of Successful Interdisciplinary Projects

This section provides several case studies of successful interdisciplinary projects on chip scale computing systems leveraging unorthodox state variables. The assemblage of project teams, a consortium of academic institutions, universities, research laboratories, and start-ups is presented. Two projects are considered, exploring neuromorphic engineering and designing bio-integrated processors.

Neuromorphic computing, the efficient handling of big data, is pursued under various approaches. As with prior technologies, special-purpose devices based on new concepts will be needed to complement general-purpose processors. Many disciplines are advancing devices based on physical systems mimicking the operation of the brain. These endeavors have achieved demonstrators substantially more capable than existing general-purpose processors, performing complex tasks with far fewer resources.

At the same time, designs and proposals of architectures, networks, and programming approaches are in rapid evolution. Networked neuromorphic systems differ from conventional systems, giving rise to new computing paradigms. The physics community is engaged in a plethora of studies to determine the capacity of various networks, the impact of topology on function, and other esoteric questions. Advances in bio-inspired learning approaches are important as energy and time are at a premium. The implementation of learning and other algorithms will also demand heterogeneous systems, involving an ever-growing mix of processors capable of different tasks and running code targeting their properties. These horizons naturally motivate the involvement of theorists and experimentalists from diverse fields.

The goal is to build a complementary education and training network, bringing together leading institutions, knowledge, and resources across disciplines relevant to neuromorphic systems. Knowledge transfer between disciplines is facilitated, including computer science, mathematics and theoretical physics, biology, neuroscience, and device physics and engineering. The importance of integrating knowledge across disciplines is highlighted by neuroethology, studying how the brain evolves to accomplish differently. Asynchronous, loosely coupled, transient, perturbed dynamics governed by local interactions are emphasized, contrasting with traditional codes studied in computer science.

The interdisciplinary approach ensures knowledge transfer within the domains of computer science, mathematics, biology and neuroscience, and device physics and engineering. Understanding the kernel of the neuromorphic revolution allows the overlap of research programs in the five disciplines. Within the computational, theoretical, and mathematical component, the development of techniques to quantify and exploit the nonlinear response of dynamical systems has the potential to greatly reduce the complexity and energy cost of learning algorithms. Systems that are intrinsically complex and operate close to bifurcation survive perturbations, enhance efficiency, and exhibit outputs approximating a broad class of functions. In addition to the development of standard mathematical tools, the removal of description mismatches, greatly inhibiting the transfer of knowhow from scientific communities, is pursued.

12.6. Future Trends in Computing Technologies

Many alternative computing systems are being explored to meet the high demand for computing systems posed by machine learning AI workloads. These alternatives span multiple scientific disciplines and include a diverse range of systems and mechanisms. Each alternative has merits and challenges that may enable or hinder its wider adoption in the foreseeable future.

Advances in programmable quantum chips provide great promise for significant performance gains in scientific simulation and other areas, as well as questions of interest to the foundations of all physics. Building practical quantum chips with several dozen entangled qubits will be an expansive necessary first step to building useful quantum chips.

Neuromorphic engineering taps the past and present of the biological basis of computation. Integration of programmable nanodevice arrays designed to mimic post-synaptic neuron phenomena, forming a nonlinear computational model, is wed to high-level programming languages and data flow architectures. This area has a wide range of potential applications but faces a notable market challenge with the difficulty of persuading silicon designers to adopt a fundamentally new architectural model.

Bio-integrated processors complement neuromorphic systems. Predictive monitoring of chemical and biological states will benefit from integrating sensor nanoelectronics with probabilistic natures and reservoirs that can learn as a natural part of their dynamics.

Disease diagnostic chips and chips that leverage an organism's own immunity to defend against disease merit consideration for both the positive impact they will bring and the ethical challenges they invoke. Chip designs leveraging the inherent distinction between self and non-self may provide an intriguing new model of computation. However, the complexity of and fitness of these models for dealing with real-world problems, as well as ethical use of such powerful devices, requires deeper contemplation.

12.6.1. Predictions for Quantum Computing

Scientific progress is usually based on predictions made by the specialists in the corresponding field. These predictions on one side should be realistic, taking into account known principles, and on the other side should point out the astonishing potential of future development. In what follows the near and nobody-expecting future for quantum chips and computers, neuromorphic engineering, and bio-integrated processors will be considered.

The harvesting of quantum chips and simulations. Small quantum computers and simulators are emerging. It is now possible to implement quantum algorithms and protocols on systems with 10-20 qubits, and operational systems with 50-100 qubits will be available or perhaps have already been created. There will be a lot of joint engineering work ahead to improve the new type of tools for research in quantum computing, quantum simulators, and other applications of quantum information technologies. Besides hardware and software, it will be necessary to construct and develop projects for quantum algorithms and protocols. Focused long-term research in these new directions will be really fruitful and progress in other fields. The proposals made at a very early stage, such as testing quantum advantage, applications in chemistry and condensed matter, and more, will slowly develop and gradually be realized. At that time the systems developed above will hardly be more complex than those used above OLED displays.

12.6.2. The Role of Neuromorphic Chips in Future AI

The human brain can learn and reliably respond to millions of stimuli in just a few hundred milliseconds, while computers are limited in their ability to analyze big data within a meaningful timeframe. A significant part of this superiority is due to the parallel organization and in-memory data storage of biological neurons. While colossal advances have been achieved in hardware and algorithms, the core distinct characteristics of the brain cannot be fully employed and explored in standard computers. Massively parallel stochastically operating processors with time-continuous dynamics, which are tightly networked with billions of synaptic connections, are required to enable machines that are capable of learning in real-time. It is a long-term goal of computer science to construct machines that emulate the human brain and thus mimic its extraordinary performance in recognition, categorization, and adaptive control tasks. The construction of such machines is termed neuromorphic engineering, and the term also covers the application of unconventional computing devices inspired by biological information processing. With this focus, neuromorphic engineering could turn into a disruptive technology in a similar way to conventional microelectronics.

Early academic works introduced unconventional cell types, synaptic implementation principles, and the application of methods. It set the stage for introducing novel devices and their application in neuromorphic engineering. This category includes nanoscale devices exhibiting stochastic dynamics, resistive switching devices, and integration of memristors on the same die as components. The general approach is continuing to be seen in non-traditional computing substrates. With these innovations, new and unprecedented cells can be investigated, and a multitude of novel concepts can be explored. The demonstration of a system capable of answering real-time queries on large visual stimuli is also addressed. The current challenges comprise devices' reliability, noise suppression, and gain control in the analog domain, the development of scalable architectures, the establishment of algorithms exploiting the hardware capabilities, and the construction of useful applications. Many groups undertake significant acceptances in these emerging fields within computer engineering, physics, and biotechnology. The proliferation of neuromorphic hardware and system-level architectures, traditional and innovative devices, as well as potential applications in a plethora of fields from artificial intelligence to food safety and invasive species detection is demonstrated.

12.6.3. Emerging Trends in Bio-Integrated Systems

The possibility of bio-integrated electronic systems, such as circuits and computers with embedded biological parts, presents great potential for the future. A brief survey is provided here of a few selected devices being developed, following a look at some of the underlying philosophies and potential applications in bioelectronics.

Neuro-pixel arrays made of neurons growing on a substrate with electrodes embedded in it have been previously proposed. These devices use spikes from the neurons or pre-synaptic currents as signals, and spikes cause postsynaptic currents by means of matrix multiplication of the spikes and the weight vector. Behaviour similar to that of hardware spiking neural networks is re-created in a biointegrated manner. Testing with hippocampal cultures and in silico modelling suggest that these technologies could offer significant advantages in chronic temporal memory acquisition, similar to larger mammalian brains compared to rodent brains using RSN, improving the autonomy of implanted technologies.

Bioelectronic sensors are envisioned, for example relying on enzyme biocatalyzed reactions for detection, with the sensitivity provided through an ionic-to-electronic signal conversion. A special approach involves the untargeted broadened analysis of biofunctionalized proteins, the detection of which is achieved in-situ on a flexible transistor array. The transformative advantage of bio-integrated devices in such sensors is potentially tremendous, allowing powerful early feedback systems to be constructed, e.g. for predicting and preventing events such as seizures.

Neuromorphic engineering offers an opportunity to use the principles of biological information processing systems to develop new neuro-inspired computing devices. Such devices and architectures can overcome the limitations of computing devices based on CMOS-devices and von-Neumann architectures. One of the many drivers in this space is the emerging need for low-latency, low-power computation for edge devices such as robotics, drones, ASI detectors, high-throughput genome analysis, and many more . In society today, many IoT devices sample heterogeneous sensory data like audio, vision, data streams from accelerometers, etc. Traditional computing solutions currently in flight today for edge devices do not scale from these scenarios owing to increasingly large data; von Neumann-architecture computers face the fundamental limiting factor of increasing numbers of transistor switches on chips. There is therefore a key opportunity to develop novel devices and architectures that are fundamentally different.

12.7. Societal Implications of Advanced Computing

Novel computing technologies will play an important role in future societies. They will introduce new challenges but will also offer opportunities to overcome existing problems and to solve problems that were previously considered unsolvable. Large-scale tax regulation or government budgeting can serve as examples. Advances in artificial intelligence and advanced computing hardware will be crucial to develop preparation approaches that can save completed time. Novel dedicated hardware will be needed for this purpose, together with associated software for their control, training, interfacing, and integration in larger systems.

Traditional artificial intelligence relies mostly on digital processors in the von Neumann architecture. This architecture is characterized by speed and memory limitations, preventing further speed improvements regarding digital general-purpose hardware. Emerging hardware will follow varied implementations that diverge from von Neumann architectures either through no longer relying on electrical charges, and instead relying on other mechanisms, or employing exotic properties. It is unclear whether substrates closer to implementation will become dominant or whether it might still be an open race. However, the prevalent approach of focusing investment on mathematical formalisms that are already complemented with the most superior hardware can be questioned. This is especially the case for prospective target applications within pervasive systems in terms of number of instances and simultaneously occurring entities, dimensions, environments, processing latencies, and needed robustness.

An argument for following an engineering-informed approach in selecting potential formalisms provides market opportunities for smaller hardware engineering enterprises. Co-evolution between novel mathematical approaches and newly devised dedicated hardware is expected to give rise to further novel systems and maybe breakthroughs in various areas. Such co-evolution will follow a concatenated strategy involving hyper-parameter optimization on dedicated hardware generating novel forms and individual adaptations of equations and logically sound models, alongside hardware re-engineering and evolution producing dedicated hardware at different abstraction levels. Likewise, hardware engineering should explore possibilities to dispense with software implemented learning processes.

Advanced computing hardware is expected to obey vastly different physical principles and to significantly differ in speed, power consumption, miniaturization, robustness to hardware-induced failures, parallelism, and mismatch. Some models and variational formalisms might have close-knot hardware possibilities that cannot be handled by any of the other formalisms. So far mostly orthogonal approaches have been taken. Open questions that might guide future research include how to classify substrates in functionally meaningful ways regarding underlying principles and how materials properties relate to computability. Similarly, for a better understanding of properties of dedicated hardware, it is essential to find a formalism describing the performance of a mathematical approach regarding a task independent of its mathematical nature. Modeling formalism performance might come with its own set of unexpected discoveries.

12.7.1. Impact on Employment and Workforce

Advances in deep learning, massively parallel processing, sensors, and storage have fueled the rapid adoption of artificial intelligence and machine learning across many sectors. Such advancements must be complemented by hardware efficiency to ensure sustainable growth and utility. As computational requirements grow exponentially, there is a growing consensus around the need for architectural and technological paradigm shifts for both digital and analogue scaling. Even with advances in extreme scaling CMOS and materials innovation reducing energy costs of standard digital workloads, the increasing complexity of applications, such as deep learning and generative AI, will inevitably lead to compute surpassing memory bandwidth, potentially placing a hard ceiling on the continued improvement in energy efficiency of generic computing subcircuits. This trend is further exacerbated by the ever-expanding footprints and costs of data centres housing traditional workloads. Analog and in-memory computing architectures, efficacious devices, and associated adaptive algorithms have emerged in recent years to potentially ensure continuity beyond the physical limits of silicon scaling.

Computing is a crucial engine in an increasingly digital world, with enormous social and economic implications. While the key challenges of efficiency, non-linearity, complexity, and very large sizes of computing systems remain, modelling and simulations of the physical processes necessary to implement computation on different energy and time scales have become significantly more sophisticated. New and unconventional devices and systems exploiting these processes are being developed for both classical analogue and emerging quantum paradigms of computation. Robust, general algorithms for these new devices and systems, with an emphasis on their implementation on existing ecologically efficient devices, are also a focus of intense research activity.

These updates on tasks, benchmarks, devices/systems, and algorithms arise amid a dizzying array of choices for each of the components of the roadmaps. Freeing devices/systems from the burden of digitisation is crucial since power is a crushed variable in the quest for energy efficiency. Robust thermalisation/refractory states need to be made exploitable, stressing the need for separate write/read/erase strategies as well as tolerant architectures. The urgency of broadening access to non-traditional systems is highlighted to test the scalability of pseudo-random networks with many-connected oscillator nodes, with an emphasis on benchmarking. This work shows that, as the use of AI expands, so too do worries about its ecological impact and biases.

12.7.2. Privacy and Security Concerns

In a world flooded with AI and machine learning algorithms, a data-leakage incident could not only destroy the worth of millions of euros, but it could also spark a loss of credibility for a scientist, a research group, a company, or a country . Despite many cryptography and data protection efforts, concerns are mounting regarding unpublished algorithms being captured through side-channel attacks, like storing and monitoring electromagnetic emissions, or through the analysis on the inputs and outputs of a function in the case of model extraction. Data poisoning and Trojan attacks have proven to be a possibility even in training of AI nets, with these attacks resulting in control of unfavorably biased decisions. Understanding the privacy risks stemming from an AI algorithm, a biomarker, or a life-science data, preventing the leaking of information, and improving technology and know-how security are crucial in the AI era. Methods for both post-processing prevention of data leakage and prevention of attacks and data monitoring will be needed. Likewise, the massive adoption of neuromorphic ICs and XNNs in the Internet of Things and automotive applications will elicit additional sensors against electromagnetic emissions and possible privacy breaches. Efforts will be necessary in coming to MTBF predictions and in the design of fail-proof functionally redundant XNNs with detection counters against both bit-flipping and Trojan attacks.

An overarching concern will go beyond the privacy of the specific logic function of a deep net, or of the specific gain and weights of a trained XNN, and will regard the need for multilevel protection of knowledge and know-how. Global efforts will be required for prevention or limited usage of very large scale training of generative models and graph neural networks trained on sets of personal data.

12.7.3. Potential for Social Change

While neuroscience research enables surrogate philosophical realms, efforts to integrate in mental life might raise irresistible social demands. This is because preceding social changes usually reinforce metaphysical conceptions that inspire the newly, bio politicized social wishes. Such cultural milieu prefers irreversibility over ulterior theorization by neutral inquiry. Thus, public fear-managing settings via heuristics based on ‘artificial’ versus ‘natural’ develop, leading to superficial and ideologized debates. Nevertheless, as language fully capitalizes on the biomechanics of thought, the science of human psychology precludes abstract knowledge margins. Some philosophical conceptions initiated by a mechanization of reasoning attempt to construe ubiquitous culture passages. Accordingly, future consciousness-affecting devices must be at least neutral on some features fundamental to thought activity. Thus, a knowledge regime of more singular standards must occur, comprising techniques able to model accidental mental endowments by building parallel counterpart cognitive machines. These would be intelligible on an abstract level to the bio-sensitive techniques, through which third-party mechanization of a default mental life would be unfeasible at least with respect to some essential mental truths. Such preventive article displays that neuroscientific research based on either Hartrian propositional knowledge or ordinal signaling mechanistically observable structures naturally arrives at post-empiricist versions of the finitudinal metaphysics rejected by phenomenology, radically abiding translations across diligence frames. Thereby, neurophilosophy might detect patterns of concept laws opposing thoroughly or making non-perceptually plausible cultural mechanisms possible. Nevertheless, even in the latter case, several unavoidable scenarios would loom prior to the advent of general conscious-affecting techniques, including the necessity of adopting some access-precaution regime up to which original cognitive machinery cannot reach and perhaps risks could be valently perceived.

12.8. Conclusion

This roadmap discusses recent progress in unconventional computing paradigms which exploit advanced nanotechnology and a research agenda for new logic, interconnect, and memory devices that can handle this information explosion. Diverse devices and emerging science which underlies them are described, including their design challenges posed by physical limitations; these may be addressed by new materials, jagged geometries, and/or non-equilibrium operation; all device classes ultimately require novel computational architectures to exploit their unique physics. Directions in hybrid materials and device settings, which might enable innovations in non-local nonlinear processing, high-fidelity quantum circuits, spiking/reservoir and low-power trained networks, and simulation of emergent states in quantum matter, are highlighted. This emerging phase of coupled progress in new science, materials, devices, and algorithms can empower groundbreaking advances in adaptable context-sensitive machine intelligence and megaFLOPS per watt semiconductor chips with tiny footprints, which will better integrate computing with controls, sensing, and actuation in the energy-efficient cyber-physical Internet of Things.

Beyond CMOS, novel devices derived from electrodynamics and thermodynamics of non-equilibrium systems offer new computational capabilities that outperform conventional silicon transistors. In spintronics, the HTTP of ferromagnets encodes 1's and 0's, coherence controls switching rates, skyrmion twist generates a foray, and a nano-oscillator group fires solitons on amperes. Coherence in memristors generates new types of neural networks which riff on proposed math to solve NP problems. Glassy thermodynamics allows extreme parallelism with nanoMacs waived quantum devices. Besides exceeding exponentials, devices derived from fractals shrink footprint by orders of magnitudes but offer no speedup. The provably universally efficient R paradigm re-formulates functions as finite unitary operations on n-particle entangled states. Unlike any non-universal model, it can perform any conventional computation faster. Requiring the discrete Fourier transform of qubits, both quantum and ion-trap approaches are likely to work. Outcome probabilities can be read-out by a specialized classical computer or revealing an entire probability distribution directly. Workspace moves us beyond non-locality to re-insert vanished power, enhancing effort-based predictions while uniting mathematical and physical facets. Next-generation hardware platforms are now matured and being integrated with task-solving algorithms. Future research directions include special-purpose real-world chips and delayed querying where question format is bi-directional.

12.8.1. Future Trends

These five example systems showcase the diversity and potential of such devices that have been considered for future computing applications. In each example, a system design was elaborated to evaluate the performance, in many cases through collaboration between multiple institutions. Some systems considered novel functions such as accelerating quantum processing, using light intensity modulations instead of states, or handling multiple programming schemes. Others focused on the emphasis of novel fabrication routes for scaling up the implementation and a better integration with platform-standard materials or methods. In all cases, modeling was instrumental in quantifying the systems, advancing the developments in proof-of-concept prototypes, and enabling the early stages of technology transfer and industrial interest.

Quantum computing systems based on a potential future quantum chip show ample potential. Being the farthest on the path from research-to-industry, first rounds of funded hardware development are actively pursued by leading industrial players. Hybrid quantum-classical schemes and platforms are presently the focus of recent initiatives, however, today's photonic quantum chips are still far from ideal performance.

Faster optical size frequency combs could alleviate some production strains. Silicene and germanene precursor materials could allow the production of better-targeted chips. The chip modeling tools developed partly address the manufacturing shortcoming, however, materials and time-constraints limit the applicability of these models to such systems. Nanowaveguide-exciton-polariton systems offer unprecedented applicability in non-linear photonics. The many-body effects describe perfectly the slow, dissipative motion of exciton-polaritons in continuous wave regime. However, the implementation of those models remains a challenge in time-dependent implementations and for the time scales relevant for such devices.

In neuromorphic engineering, there is a compelling good conventional path towards the future, which is strictly orthogonal to that of the other listed systems. A comprehensive theory-based approach could provide fully-calibrated solutions, already today, for large-scale implementations at low-risk and unseen performance that offer higher fidelity hardware co-design.

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