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Views & Comments

Analysis of Potential Disruptive Technologies in the Electronics and Information Field Towards the Intelligent Society

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1. Introduction

In the era of the new century, driven by the development of the intelligent society, the integration of the field of electronics and information with various technical fields and industries has accelerated and become the major driving force for a new round of technological revolution and industrial transformation. This has advanced the profound adjustment of global technology, industry, and division of labor as well as reshaping the innovation and competitiveness of countries around the world. Electronics information has received the most concentrated research and development investment worldwide and has been actively advancing and playing a leading role in dissemination. Naturally, it has become an important strategic area in which the world's scientific and technological powers seek economic advances and competitive advantages.

Given the technical needs of the intelligent society (e.g., universal connectivity, real-time broadband, and ubiquitous intelligence), the digitization, networking, and intellectualization trends of the information and electronics field in the post-Moore era are becoming increasingly evident and have led to several disruptive technologies. At the level of basic research, quantum electromagnetics, integrated circuits aiming for a breakthrough of Moore's law, and cyber–physical-tightly integrated information technologies will serve as the basis to foster innovation, as shown in Fig. 1. Breakthroughs in emerging technologies (e.g., the next generation of high-speed computing and the sixth generation mobile networks (6G) technology) [1], may be applied broadly to various industries and may have far-reaching impacts on society. The innovations of cross-integration and disruptive applications [2] (e.g., integrated space–earth networks) will change the landscape of existing applications to an unimaginable extent.

The field of information and electronics is concerned mainly with the generation, transmission, processing, and utilization of information and relies on basic theories, materials, and technologies. Disruptive technologies in such a field are characterized as fundamental, interdisciplinary, explosive, and cross-integrated. Fundamental refers to the incubation of new technologies from basic theories. Interdisciplinary implies encompassing multiple technological directions and spreading into multiple application domains. Explosiveness refers to rapid application expansion and industrial eruption. The cross-integration of technologies (e.g., information perception, processing, and high-speed communication) promotes innovative applications (e.g., the Internet of Things and smart cities), which in turn enables the evolution from an information society into an intelligent society. This paper examines potentially disruptive technologies using examples from carbon-based materials and information metamaterials, photonics–electronics technology, computing in memory (CIM), and artificial intelligence (AI).

2. Carbon-based materials and digital information metamaterial technologies

Silicon-based chips are the cornerstone of modern information technologies. However, they have reached the physical limits of Moore's law and the ceiling of their performance. In 2018, the International Roadmap for Devices and Systems listed carbon-based nanomaterials as an option for future integrated circuit technology to continue the trend predicted by Moore's law [3]. Since then, semiconducting carbon nanotubes (CNTs) have demonstrated promising potential to build carbon-based chips. Compared with traditional bulky silicon and gallium arsenide (GaAs)

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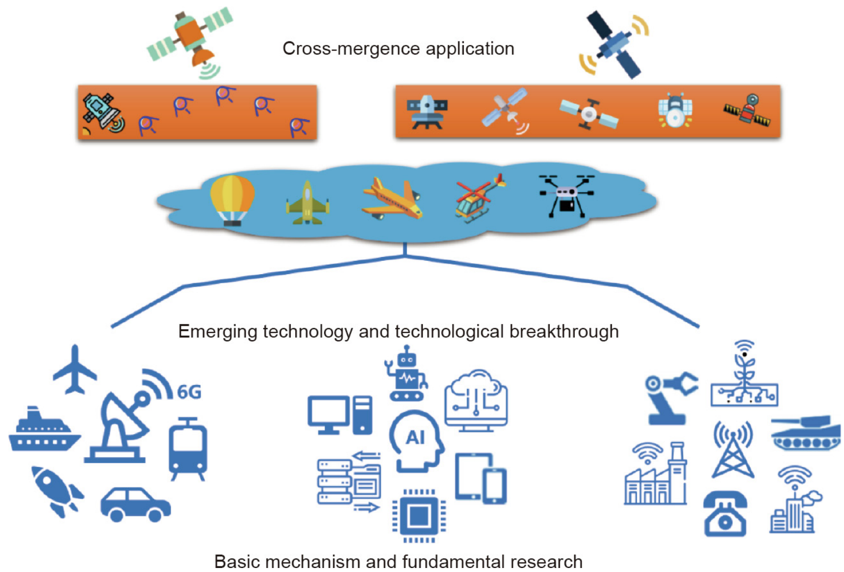

Fig. 1. Potential disruptive technologies in the field of electronics and information. 6G: the sixth generation mobile networks; AI: artificial intelligence.

materials, CNTs have the characteristics of low power consumption, high carrier transport (up to $10^5\ cm^2{\cdot}V^{-1}{\cdot}s^{-1}$) [4], and ultrathin bodies (one-dimensional semiconductors). These characteristics improve the energy efficiency of carbon nanotube field-effect transistors (CNFETs) by an order of magnitude compared with those of silicon-based field-effect transistors. A beyond-silicon microprocessor composed of CNFETs fabricated by a standard industrial design process was demonstrated to overcome nanoscale defects across the entire wafer substrate. In the future, the precise control and batch preparation of ultralong CNTs, as well as the preparation of high-density and high-purity CNT arrays, will enable the digital fabrication of very large-scale integrated circuits based on CNFETs, thereby laying the foundation for the mass production of the next generation of chips with significant performance improvements.

A metamaterial is a man-made material that is engineered to have properties that do not exist naturally. The digital information metamaterial proposed by Academician Tiejun Cui of Southeast University controls macrophysical properties [5] (e.g., electromagnetic, optical, and acoustic properties) that are unavailable in traditional material through the precise design of the geometry, size, and arrangement of the microstructure units. In particular, the basic idea is to apply digital control signals to each microstructure unit to control its electromagnetic resonance characteristics. When electromagnetic waves interact with the digital metamaterial, they become encoded with the digital control information. In this way, the phase, amplitude, beam direction, and orbital angular momentum of the electromagnetic wave can continuously be changed by digital control signals, and the digital information metamaterial can perform modulation, transmission, and beam agility with only one component. As a result, digital information metamaterials can transform the modality of imaging, wireless communication, intelligent perception systems, and so forth [6,7].

In recent years, information metamaterials have been used to realize time-coding and spatial–temporal-coding digital metamaterials and have operated in conjunction with the digital convolution theorem and Shannon information entropy [8,9]. A 360°-phase quasicontinuous tuning and nonlinear polarization synthesis have been proposed, and electromagnetic wave energy can disperse in space and frequency domains under digital control. Moreover, these materials can break reciprocity and isolate wave reflections in the space and frequency domains, where these nonreciprocal effects can be dynamically controlled. At present, information metamaterials have realized field-programmable holographic imaging, which can independently control the near-/far-field modes of electromagnetic waves, as well as the transmission and reflection modes of electromagnetic waves under different polarizations, and are expected to realize holographic imaging from microwave to terahertz and optical frequency bands. More importantly, a wireless communication system with a minimalist architecture has been realized, in which information metamaterials have been developed with multiple functions, such as information loading, information transmission, and communication multiplexing technology in traditional systems. Information metamaterials can manipulate electromagnetic waves dynamically and arbitrarily but require manual control to switch among different functionalities. Therefore, information metamaterials are expected to realize intelligent electronic devices, as shown in Fig. 2. At present, the intelligence of metamaterials is embodied mainly in adaptive metamaterials and in combination with AI.

3. Cross-photonics–electronics technologies

The development of information and electronic engineering has long been based on the use and development of the electromagnetic spectrum, which is the core resource in the field—from microwave to infrared and from infrared to visible light and ultraviolet, each spectrum corresponds to its unique information generation and processing methods. However, with the development of electromagnetic technology, technologies in various spectra have gradually forged a trend of cross-integration, and optical and electric technologies are constantly infiltrating each other and developing together.

Microwave photonics technology is produced by photoelectric integration, and it combines light emission, modulation, and detection with silicon-based chips to develop a silicon-optical-centered electronic device. Based on this, researchers have developed novel radar, imaging, and communication systems with the architecture of "light" transmission control and "electric" information processing as well as a series of breakthroughs in microwave photonics technology. In 2020, Intel demonstrated a copackaged Optics Ethernet switch that integrates a $1.6\ Tb{\cdot}s^{-1}$ silicon optical engine with a $12.8\ Tb{\cdot}s^{-1}$ programmable Ethernet switch, providing a new technology to support future network bandwidth expansion [10]. A team at Sun Yat-sen University proposed a high-speed silicon optical control chip that for the first time integrates a lithium niobate film and a silicon-based chip. This chip considerably improves the performance of silicon optical chips, for the first time achieving wireless communication rates above 1 $Tb\cdot s^{-1}$ and setting a world record for wireless communication transmission [11]. In addition, the development of integrated photonics has enabled the photonic processor to have higher unit area computing power and better potential scalability. In 2021, the Lincoln Laboratory of Massachusetts Institute of Technology demonstrated a surface-electrode ion-trap chip using integrated waveguides and grating couplers that provides a complete and individual control method for a larger number of ions in a quantum information processing system [12].

The terahertz spectrum is located between microwave and infrared and has become a spectrum bridge across photonics and electronics, as shown in Fig. 3. Ultimately, terahertz technology will become a cross-integration of optical and electrical technology. In recent years, terahertz technology has been heavily investigated to meet the demands for broadband mobile communication, the radar of high frame rate and high-resolution, rapid security checks, and material and bioanalytical technology.

Terahertz communication has been identified as one of the eight potential technologies of future 6G wireless communication technology because of its moderate beam width, easy tracking, extremely wide bandwidth, and strong privacy. Although the application of various new materials and structures has made a leap forward in the performance of terahertz communication devices, existing terahertz devices still face many challenges in achieving the requirements of ultra-high-performance terahertz communication technology. First, molecular absorption and free-space losses, as well as the limited transmission power of terahertz devices, limit the application of long-range terrestrial communications. Moreover, the energy consumption on the transmitter side of terahertz communication is low, but the total energy consumption is still high due to the high energy consumption of baseband signal processing. At the same time, in terahertz communication, devices

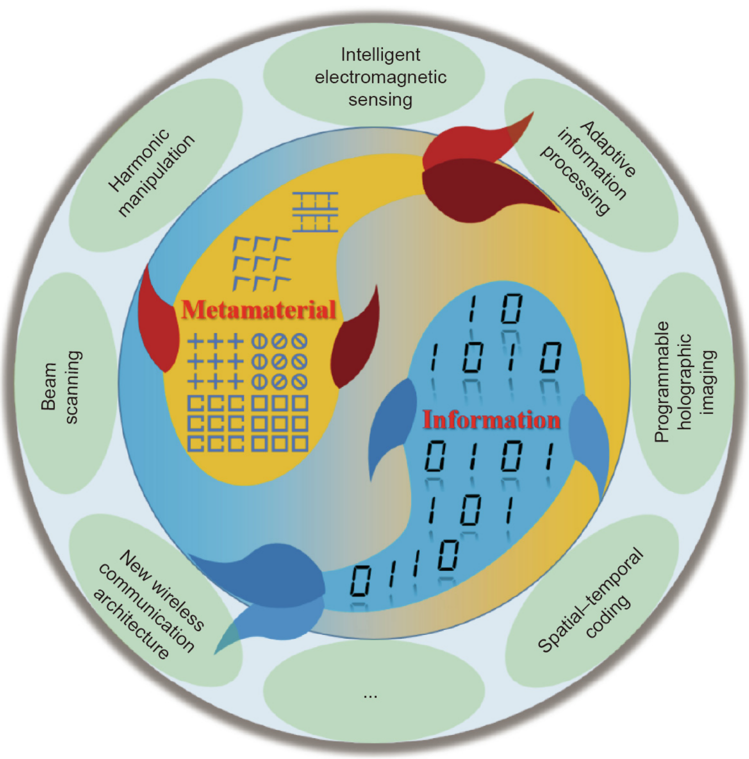

Fig. 2. Digital information metamaterial technologies.

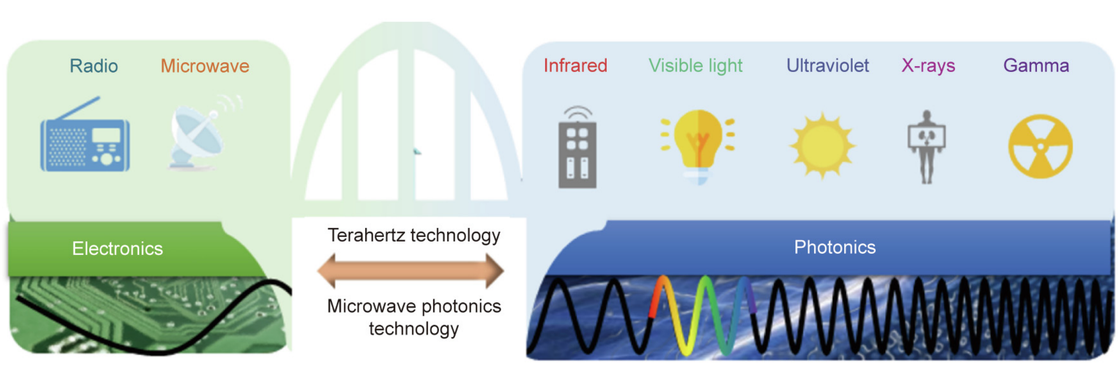

Fig. 3. Cross-photonics–electronics technologies across the electromagnetic spectrum.

are more likely to overheat as the transmission power increases, thus placing higher demands on the micro-heat-dissipation technology of the devices. Finally, because terahertz communication technology still faces the problem of a lack of communication standards such as materials and transmission power when combined with emerging technologies, cross-disciplinary cooperation has a long way to go.

4. Reversible CIM with two-dimensional (2D) devices

The development of technologies such as AI and big data has pushed society into the era of intelligence. The advent of novel concepts in social development, such as smart cities and city brains, has spawned massive amounts of data and induced urgent needs for high-speed intelligent processing of large quantities of data. The physical separation of logic and memory functions in conventional von Neumann architecture results in a "memory wall" and a "performance wall." Consequently, computing power and the resulting energy consumption have become new bottlenecks in the development of the intelligent society. Recently, CIM has emerged as a promising alternative in which logic operations are performed inside memory units. CIM has been demonstrated [13] with volatile memories, such as static random-access memory and dynamic random-access memory, as well as nonvolatile memories, such as flash, phase-change memory, and resistive random-access memory.

The continued enhancement of computing efficiency faces another major challenge: the reversibility of computing. The von Neumann–Landauer (VNL) limitation sets a fundamental limit of energy consumption for logical operations: Erasing one bit of information consumes at least $k_B T \ln 2$ of energy (k_B: Boltzmann's constant; T: temperature). For logic gates, such as "AND" and "OR," one bit of information is erased during each logic operation, leading to inevitable energy consumption. The Fredkin gate is a reversible logic gate that can overcome the VNL limitation and perform complete Boolean operations, thereby offering a new digital computing approach. Combining reversible logic with CIM can create a new paradigm in advanced computing (Fig. 4).

2D materials (including carbon-based materials) have exceptional electrical and mechanical properties and are therefore highly promising for building future CIM and reversible computing devices. These materials have already been used for realizing parallel in-memory data search and logic-in-memory devices [14]. These 2D devices have ultrasmall size and ultralow power consumption, and can be integrated with other materials and devices, thus offering exciting opportunities for create future reversible CIM applications.

Yet challenges remain for 2D materials and devices for reversible CIM to be used in real-world applications towards a smart society. First, different 2D computing devices exhibit different advantages and limitations; thus, the 2D device that would be most suitable for such reversible CIM remains to be identified. Second, while thin-film growth of 2D materials has been progressing rapidly at the wafer scale, these materials still suffer from uniformity and reliability issues, which may affect device performance. Third, the heterogeneous integration of such devices on a large scale and with external circuits still faces several technical challenges. Therefore, continued research efforts are necessary to further clarify the computing mechanism, optimize the material growth technique, and facilitate the integration capability. Once these key hurdles are overcome, we envision that ultra-low-power and compact 2D devices enabling reversible CIM will be broadly adopted in the future smart society.

5. Big-data-driven AI technology

In the intelligent society, the ternary space (i.e., cyber–physical–human space) continuously produces massive quantities of data in different forms, exhibiting explicit or implicit interaction patterns between individuals and representing human lifestyles, behavior patterns, and social trends. Big data [15] from the ternary space is reshaping the current computational methodology for scientific experiments, model induction, and simulation, thereby promoting the establishment of a new paradigm in data-intensive computing. This AI-based computing paradigm driven by big data takes advantage of AI techniques to conduct in-depth analyses of big data, explore the intelligent form of its hidden patterns and laws, and utilize theoretical methods and supporting technologies to synthesize big data into knowledge and decision-making, as shown in Fig. 5. The computing paradigm of "from data to knowledge, and from knowledge to decision-making" can effectively integrate different sources of knowledge and data for services while facilitating knowledge extraction and utilization through in-depth analysis of data processing from different sources and realizing data collection and aggregation by positioning and connecting various data sources. Hence, this computing paradigm is characterized by improving generalizability, resistance to attacks, and process inference as well as achieving a complex system architecture.

Therefore, theoretical innovations in AI driven by big data, such as unknown modeling, model robustness and interpretability, games under incomplete information, and human-in-the-loops, will help AI leap forward into strong AI [16] and provide technical support for autonomous unmanned systems, group collaborative intelligence, and hybrid enhanced intelligence. Developments in AI driven by big data have recently been used in various ways to implement self-adaptive, self-learning, self-evolving, safe, and verifiable intelligent models and basic theoretical algorithms, ultra-large-scale high-performance machine learning paradigms, and other technical research. AI can improve the performance of unknown models. For example, we can use it to optimize the design process of carbon-based materials and metamaterials. In addition, it can also be used to help realize games against group intelligence and empower machine learning with computing architecture. Big-data-driven AI will promote the scientific research method of "data + causality" [17] to become a 4+ paradigm. The

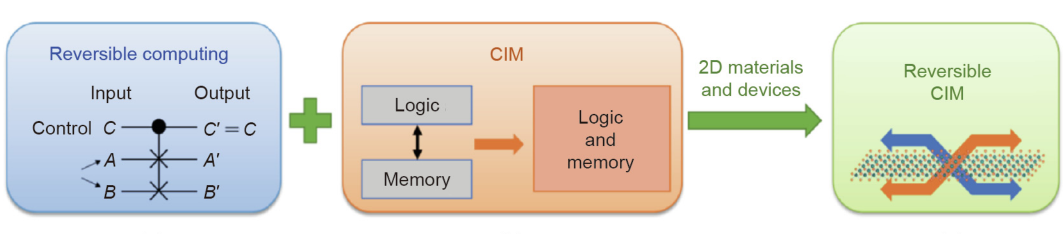

Fig. 4. Illustration of reversible CIM. (a) Fredkin gate can be used to build logic circuits. A, B, and C refer to the input of the Fredkin gate; and A', B', and C' represent the output of the Fredkin gate. (b) CIM can be combined with the unique capabilities of 2D devices to realize (c) reversible CIM, enabling a new computing paradigm.

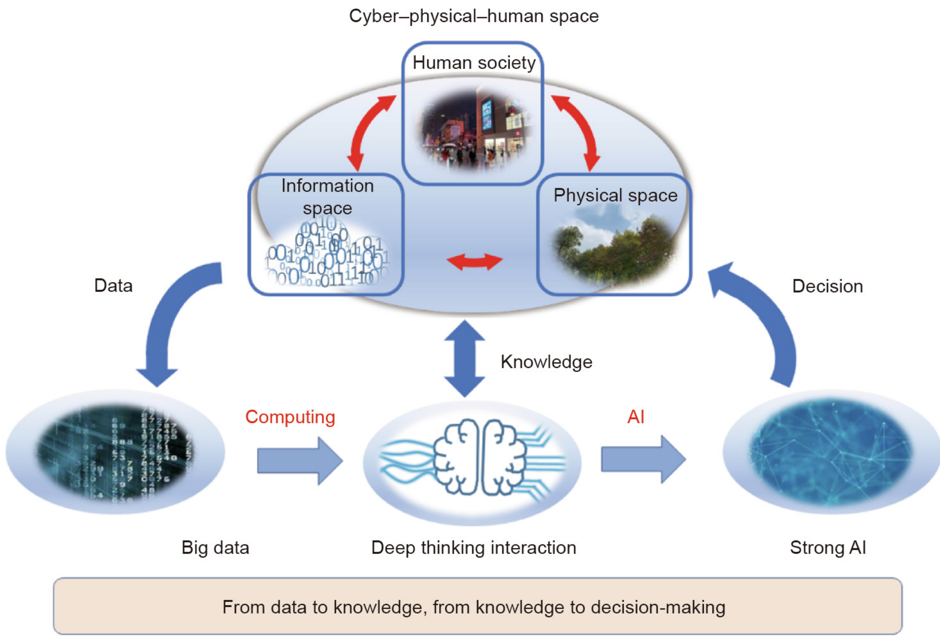

Fig. 5. Illustration of big-data-driven AI technology.

core of the 4+ paradigm is to study the model method on the basis of knowledge guidance and data-driven and experience learning and to support the intelligent society with new theories and techniques with knowledge-guided deduction, data-driven induction, and environmental feedback loop planning.

However, current AI techniques still have problems such as the poor adaptability of perceptual intelligence, unclear cognitive mechanisms, and weak development of general AI. There is an urgent need for AI to make algorithm breakthroughs to form a new generation of safe and reliable intelligence. The field has the following hotspots: how to combine data-driven, knowledge-guided, and experience learning mechanisms for a more interpretable, stable, fair, and actionable model that can trace the output results of the model (with interpretability and causality), realize robustness to possible errors, and achieve the ability to learn about unknown modeling problems.

6. Conclusions

With the continued development of the intelligent society, emerging industrial markets, industrial technological advances, and intelligent military confrontation, a few emerging technologies have appeared in different sectors and technical areas within the information and electronic engineering field. These have formed a series of innovative technology groups, capturing the basic electronic information theory, materials, and device manufacturing processes along with the generation, transmission, processing, and utilization of information. Such innovations have great potential, leading to disruptive technologies that can influence production and human lives in general—"moistening things silently." This article highlights several directions with potential breakthroughs that are by far not comprehensive. For instance, in the field of sensing and processing, there are flexible electromagnetic materials and electronic equipment, spintronics-based devices and equipment, 2D materials, and smart sensing; in the field of communications, there is a new generation of 6G communication technologies; and in the networking field, there are space-ground integrated network information technology and blockchain technology. All of these factors are paving the way for the emergence of disruptive technologies. We believe that a series of emerging disruptive technologies in the information and electronic engineering field will have a profound societal impact and facilitate the next industrial revolution.

Acknowledgements

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References

[1] Giordani M, Polese M, Mezzavilla M, Rangan S, Zorzi M. Toward 6G networks: use cases and technologies. IEEE Commun Mag 2020;58(3):55–61.
[2] Wang Z, Tang K. Combating COVID-19: health equity matters. Nat Med 2020;26(4):458.
[3] Beyond CMOS: international roadmap for devices and systems [Internet]. Piscataway: IEEE; 2019 Aug 13 [cited 2021 Feb 26]. Available from: https://irds.ieee.org/editions.
[4] Bai H, Gao H, Ma Y, Wang Q, Wu Y. First-principle crystal orbital insights to the unusual increase of carrier mobility in zigzag carbon nanotubes induced by Stone–Wales defects. Diam Relat Mater 2020;109:108013.
[5] Cui TJ, Qi MQ, Wan X, Zhao J, Cheng Q. Coding metamaterials, digital metamaterials and programmable metamaterials. Light Sci Appl 2014;3(10):e218.
[6] Dai JY, Tang WK, Zhao J, Li X, Cheng Q, Ke JC, et al. Wireless communications through a simplified architecture based on time-domain digital coding metasurface. Adv Mater Technol 2019;4(7):1900044.
[7] Zhao J, Yang X, Dai JY, Cheng Q, Li X, Qi NH, et al. Programmable time-domain digital-coding metasurface for non-linear harmonic manipulation and new wireless communication systems. Natl Sci Rev 2019;6(2):231–8.
[8] Cui TJ, Li L, Liu S, Ma Q, Zhang L, Wan X, et al. Information metamaterial systems. iScience 2020;23(8):101403.
[9] Zhang L, Chen XQ, Liu S, Zhang Q, Zhao J, Dai JY, et al. Space–time-coding digital metasurfaces. Nat Commun 2018;9(1):4334.
[10] Intel demonstrates industry-first co-packaged optics ethernet switch [Internet]. Westborough: Inside HPC; 2020 Mar 6 [cited 2021 Jan 24]. Available from: https://insidehpc.com/2020/03/intel-demonstrates-industry-first-co-packaged-optics-ethernet-switch/.
[11] He M, Xu M, Ren Y, Jian J, Ruan Z, Xu Y, et al. High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s^{-1} and beyond. Nat Photonics 2019;13(5):359–64.
[12] Wu H, Dai Q. Artificial intelligence accelerated by light. Nature 2021;589(7840):25–6.
[13] Yao P, Wu H, Gao B, Tang J, Zhang Q, Zhang W, et al. Fully hardware-implemented memristor convolutional neural network. Nature 2020;577(7792):641–6.

[14] Migliato Marega G, Zhao Y, Avsar A, Wang Z, Tripathi M, Radenovic A, et al. Logic-in-memory based on an atomically thin semiconductor. Nature 2020;587(7832):72–7.
[15] Frankel F, Reid R. Big data: distilling meaning from data. Nature 2008;455 (7209):30.
[16] Pei J, Deng L, Song S, Zhao M, Zhang Y, Wu S, et al. Towards artificial general intelligence with hybrid Tianjic chip architecture. Nature 2019;572 (7767):106–11.
[17] Kuang K, Li L, Geng Z, Xu L, Zhang K, Liao B, et al. Causal inference. Engineering 2020;6(3):253–63.