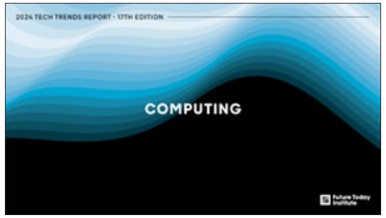
COMPUTING

Future Today Institute

FUTURE TODAY INSTITUTE'S 2024 TECH TREND REPORT

Our 2024 edition includes nearly 700 trends, which are published individually in 16 volumes and as one comprehensive report with all trends included.

Download all sections of Future Today Institute's 2024 Tech Trends report at **http://www.futuretodayinstitute.com/trends.**



THE YEAR AHEAD: TECH SUPERCYCLE

The theme for our 2024 report is Supercycle. In economics, a "supercycle" refers to an extended period of booming demand, elevating the prices of commodities and assets to unprecedented heights. It stretches across years, even decades, and is driven by substantial and sustained structural changes in the economy.

We believe we have entered a technology supercycle. This wave of innovation is so potent and pervasive that it promises to reshape the very fabric of our existence, from the intricacies of global supply chains to the minutiae of daily habits, from the corridors of power in global politics to the unspoken norms that govern our social interactions.

Driving this seismic shift are the titans of technology and three of their inventions: artificial intelligence, biotechnology, and a burgeoning ecosystem of interconnected wearable devices for people, pets, and objects. As they converge, these three macro tech segments will redefine our relationship with everything, from our pharmacists to our animals, from banks to our own bodies. Future Today Institute's analysis shows that every technology—AR/ VR/ XR, autonomous vehicles, low Earth orbit satellites, to name a few—connects to the supercycle in some way.

The ramifications are stark and undeniable. As this tech supercycle unfurls, there will be victors and vanquished, those who seize the reins of this epochal change, and those who are swallowed whole. For business leaders, investors, and policymakers, understanding this tech supercycle is paramount.

In this 17th edition of FTI's annual Tech Trends report, we've connected the supercycle to the nearly 700 trends we've developed. Our research is presented across 16 technology and industry-specific reports that reveal the current state of play and lists of influencers to watch, along with detailed examples and recommendations designed to help executives and their teams develop their strategic positioning. The trends span evolutionary advancements in well-established technologies to groundbreaking developments at the forefront of technological and scientific exploration. You'll see emerging epicenters of innovation and risk, along with a preview into their transformative effects across various industries.

We've visually represented the tech supercycle on the report's cover, which is an undulating image reminiscent of a storm radar. Vertical and horizontal lines mark the edges of each section's cover. When all 16 section covers converge, the trends reveal a compounding effect as reverberating aftershocks influence every other area of technology and science, as well as all industries.

It's the convergence that matters. In isolation, trends offer limited foresight into the future. Instead, the interplay of these trends is what reveals long-term change. For that reason, organizations must not only remain vigilant in monitoring these evolving trends but also in cultivating strategic foresight—the ability to anticipate future changes and plan for various scenarios.

Our world is changing at an unprecedented rate, and this supercycle has only just begun.

Amy Webb
Chief Executive Officer
Future Today Institute

TABLE OF CONTENTS

TOP HEADLINES

AI's demand for computational power challenges computing paradigms, driving researchers to rethink architectures and governments to rethink semiconductor policies.

01 Computing industry moves in-house

As geopolitical tensions and supply chain concerns rise, there has been a push toward on-shoring critical technologies, such as semiconductors and 6G-enabling technologies. The US and its allied nations have imposed export restrictions on semiconductors and related equipment to China.

02 AI workloads demand new architectures

The commercialization of AI requires novel architectures to manage its demanding workloads, spurring research into computer architecture design. Companies are looking to alternative energy sources like nuclear and geothermal to power data centers.

03 Organoid Intelligence Represents A New Computing Frontier

Organoid intelligence harnesses stem cell-derived brain organoids to explore learning, memory, and cognition, potentially creating a biological computer.

04 New techniques emerge for error-prone quantum computers

Quantum researchers are focused on tackling the noise and error issues inherent to quantum computing.

05 AI-centric form factors emerge for personal computing

As AI transforms how we engage with computers, businesses are exploring new interfaces and user experiences, focusing on AI-driven interactions. This includes voice-controlled wearables and portable devices with chatbots as their core, making AI more central to our interactions.

STATE OF PLAY

AI is enabling novel form factors for more natural human-computer interaction, while its intensive workloads challenge existing computing models. These developments, combined with the risks of advanced AI in adversarial hands and supply chain vulnerabilities, are leading the US and allies to reevaluate their trade relationships.

Driven by artificial intelligence, humans and computers are in a virtuous cycle: a self-reinforcing loop where advancements in one area lead to progress in the other, and vice versa. In this case, humans created computers, which improve human productivity. More advanced humans created more advanced computers and so on. As the virtuous circle goes round and round, the separate entities—humans and computers—will get closer and closer to one another.

AI's voracious computational appetite is prompting companies and researchers to rethink conventional computing architectures. The Von Neumann architecture, which propelled the silicon era to this point, is now insufficient for meeting AI's computational demands. To unlock the full potential of AI in an energy-efficient, cost-effective way, researchers are experimenting with alternative computing architectures, and they are finding inspiration by looking inward—to the human brain itself. As the most efficient computing system known, the brain's architecture is ideally suited for AI workloads.

So, researchers came up with neuromorphic computing, computer architectures inspired by the biological brain's structure and function. Just like our brains, neuromorphic computers can simultaneously store and process information, a capability that makes them more energy efficient than classical computers. Researchers at Johns Hopkins University are taking this even further. Last year they broke ground on a new computing field called organoid intelligence. Whereas neuromorphic computing aims to mirror the brain's efficiency in the design of computing systems using silicon, organoid intelligence aims to utilize the inherent capabilities of biological materials or systems for information processing. Basically, organoid intelligence uses human brain cells as a computer.

This isn't merely a matter of drawing inspiration from the brain; it's an endeavor to adapt and enhance our innate physiological blueprint to fabricate computational devices that not only match the efficiency of the human brain but surpass it in intelligence. Simultaneously, breakthrough technologies like soft implantable brain-computer interfaces are

STATE OF PLAY

facilitating the tangible integration of our biological essence into computational systems. The future of computing, it seems, is not an external tool that we engage with but rather, the future of computing is an innate element fused into our sensory perception, motor control, and cognitive processing. This vision posits a future where computing is no longer an external interaction but an integrated aspect of our very being.

To get to a future where computing seamlessly merges with the human experience, it's crucial to recognize that this technological progression won't occur in a vacuum. It is intertwined with, and frequently stimulated by, a complex mosaic of geopolitical events and international frictions. This can be observed in the mounting tensions, chiefly between the US and China, over powerful chips. The US and its allies are implementing restrictions on the export of advanced semiconductors and their manufacturing equipment to China. The effectiveness of these restrictions, however, is challenging to ensure. China has already bypassed these export controls and obtained sophisticated Nvidia chips. Additionally, technologies like RISC-V, freely downloadable from the internet, will likely become pivotal for Chinese companies and government entities aiming to rival US expertise in semiconductor design.

There is also a battle between the US and China over the pursuit of quantum supremacy. The first nation to achieve this could place the other in a precarious position from a national security standpoint. The sense of urgency is further amplified by an increasingly protectionist global outlook, catalyzed by the vulnerabilities in worldwide supply chains exposed by the COVID-19 pandemic. Consequently, governments worldwide are taking measures to repatriate the production of vital technologies, a movement that includes quantum technologies, semiconductors, and even the emerging realm of 6G telecommunications. This intricate nexus of innovation and geopolitics is a testament to our age—a time of immense change and potential, when computing not only drives our technologies but also shapes the very contours of our societal and global narratives.

KEY EVENTS

FEBRUARY 28, 2023

OI: A new scientific field

Scientists form a new field, organoid intelligence (OI), considered the frontier of biocomputing.

MARCH 21, 2023

GPU-accelerated quantum device

Nvidia announces the world's first GPU-accelerated quantum computing system.

MAY 22, 2023

Long-distance quantum internet

Researchers achieve the first long-distance quantum repeater node for telecommunications, transmitting quantum information over 50 km.

JUNE 14, 2023

Closer to quantum advantage

UC Berkeley/IBM paper demonstrates a path toward quantum advantage over classical computers.

NOVEMBER 6, 2023

US Further Restricts Chip Exports

The measures aim to tighten China's access to US semiconductor technology, a key element in developing powerful AI platforms.

LIKELY NEAR TERM DEVELOPMENTS

AI, ARCHITECTURE & ALLEGIANCE

Geopolitical tensions are accelerating some key computing developments. Expect semiconductor talent shortages as nations adjust how they manage skills for self-reliance. Also expect the rush to prepare for "Q-Day" to become more urgent as countries race toward quantum advantage. We will see more companies boast quantum-resistant cryptography as a value proposition. And as countries become more wary of supply chain disruptions, more inputs will be brought in-house. As nations do this, RISC-V adoption may increase.

Technological developments in AI are also driving near term developments. To power AI, companies are rethinking computing architectures using inspiration from the human brain and existing gaming devices. AI will soon flip the script on human-computer interaction; rather than users learning to operate computers, AI allows computers to learn to interact on human terms. With AI, the computer will adapt to the person—not the other way around.

Research and Debates on OI

Expect a surge in organoid intelligence research. Organoids may be the key to AI's efficient boost, but the convergence of AI and OI may stir ethical debates.

Chip Freedom

Expect a rise in RISC-V adopters as it transforms the chip industry. Offering freedom from costly licenses, RISC-V enables custom, application-driven hardware, making chip design more accessible, thereby lowering the entry barrier.

Surge in Q-Day Preppers

Businesses will prepare more seriously for "Q-Day"—when quantum computers can break internet encryption protocols. As China and the US both achieve breakthroughs toward quantum advantage, expect a surge in investments in this domain.

Semiconductor Skills Shortage

Anticipate a talent crunch in the semiconductor sector as countries aim to internalize production. This skill gap will necessitate refocusing, driving universities and communities to prioritize these skills.

The New BYOD Policy: Gaming Devices

AI requirements will spur non-gamers toward powerful gaming devices, prompting demand for enterprise software integration. This signals a new wave of bring-your-own-device hardware—powerful yet portable. Expect increased enterprise application integration with such devices.

AI-Driven Form Factors

Expect an emergence of new form factors driven by AI, that diverge from the conventional laptop, keyboard, and mouse setup, as AI facilitates more intuitive communication methods. We might also see a surge in specialized devices designed for specific AI applications, like dedicated translation gadgets or AI-enhanced cameras.

11 MACRO SOURCES OF DISRUPTION

Technology | Media & Telecom | Demographics | Environment | Government | Public Health | Education | Geopolitics | Infrastructure | Economy | Wealth Distribution

WHY COMPUTING TRENDS MATTER TO YOUR ORGANIZATION

Chip Talent Shortage

Semiconductor companies may face growth constraints due to a scarcity of skilled workers, which could slow innovation or production delays. These difficulties can ripple through to other industries, such as automotive, which heavily rely on semiconductors. Amid rising geopolitical tensions, companies that secure talent may gain a competitive edge.

Achieving Independence With RISC-V

RISC-V's open-source nature empowers companies to customize chip designs, catering to specific needs. Its free-to-use model makes it attractive for budget-conscious companies. This lessens dependence on particular vendors, mitigating supply chain risks and bolstering resilience. Particularly in China, RISC-V advances national objectives of curtailing foreign IP reliance and achieving semiconductor self-sufficiency.

Using AI to Design Chips for AI

AI-designed chips may increase product performance and reduce costs, shifting competitive dynamics and market shares. For talent, expect less demand for chip designers and more for AI specialists. The AI optimization of chip design could disrupt semiconductor market leadership, with innovators gaining the upper hand. Further, cost-effective chip design may spur innovation in AI-dependent sectors, leading to new business opportunities.

Portable PCs: From Gaming to the Enterprise

The portable PC market, initially fueled by gamers, shows promise for enterprise users as a lightweight, powerful secondary device. Portable PCs could soon be viewed as a BYOD option for enterprises, disrupting reliance on laptops. If optimized for business, portable PCs may find a role as compact work devices, expanding hardware and software markets.

Investment in Quantum-Resistant Cryptography

Quantum superiority poses an existential threat to business data. The first to achieve quantum advantage will be able to upend security by quickly cracking encryption or by unmasking anonymized data. Mitigating this risk will require a complete transition to quantum-safe cryptographic algorithms. Though the security challenges are daunting, solutions are emerging to fortify for the quantum era.

Unintended Consequences of Export Controls

As the US tightens restrictions on semiconductor exports, the potential for Chinese retaliation poses a threat to the global consumer electronics market. China's dominance in legacy chip production, critical for a wide range of products, from household appliances to military hardware, means these restrictions could lead to higher prices and scarcity of various consumer electronics globally.

WHEN WILL COMPUTING DISRUPT YOUR ORGANIZATION?

Forecasted Time of Impact

0-4 YEARS	5-9 YEARS	10-14 YEARS	15+ YEARS
Chip talent shortage	Person-centric form factors	6G	Physical-cyber continuum
AI at the edge	Enterprise supercloud use	Commercial BCI	Biocompute outperforms classic
Work-ready gamer devices	Quantum-resistant cryptography as a value proposition	Commercialized DNA storage	True quantum advantage
			True pervasive computing

OPPORTUNITIES & THREATS

Threats

Ethical debates about organoid intelligence's human-like cognition may impede research, delaying innovations in health care, computing, and robotics.

Reshoring semiconductor manufacturing to the United States can involve significantly higher costs compared to overseas production, requiring government subsidies and policy reforms to offset higher domestic labor and tax expenses if the U.S. aims to make domestic chip fabrication globally competitive.

With notable talent shortages in semiconductors, onshoring success requires workforce development, immigration reform, and public-private partnerships for training.

Integrating neuromorphic systems with existing computer architectures poses complex challenges for synchronizing biological cognition with digital logic requiring new design paradigms.

Organoid and neuromorphic technologies risk ethical and legal scrutiny over human-like synthetic intelligence; clear governance is needed to enable innovation responsibly.

Quantum advantage may enable cracking encryption, threatening security; global rules and norms are needed to prevent misuse while fostering continued progress.

Increasing US-China tension over quantum risks could stifle collaboration; a technology embargo could cede leadership. Cooperative policy is key to preventing a tech cold war.

Opportunities

RISC-V's open architecture democratizes chip design, empowering innovation and strategic autonomy for companies and nations, reducing reliance on external suppliers.

Applying AI to optimize chip design unlocks major performance and cost efficiencies, enabling next-gen semiconductors accessible to more applications.

Neuromorphic computing's efficiency from processing and storing data simultaneously is a breakthrough for energy optimization vital for sustainability across industries.

Neuromorphic chips' brain-like adaptability can revolutionize machine learning, making algorithms more robust and powerful for transformative AI applications.

Quantum internet provides virtually unhackable communications, realizing enhanced data/infrastructure security to protect information at unprecedented levels.

Quantum-as-a-service opens quantum's potential to more industries and researchers, fostering innovation and progress toward real-world impact.

More efficient AI edge models expand access for new applications and users, driving innovation and economic opportunity by democratizing transformative technology.

INVESTMENTS AND ACTIONS TO CONSIDER

1. As AI permeates enterprise apps, modify software and operating systems to support mobile form factors like gaming PCs, which already offer advanced portability and processing that mobile workers will expect. Enable apps on compact yet powerful devices, and support policies like BYOD as gaming converges with productivity needs.

2. For enterprises using hybrid and multicloud, consider implementing the supercloud to save developers time managing complex multicloud environments. Supercloud abstraction layers integrate disparate clouds into one platform, handling management overhead so developers can focus on revenue-generating activities.

3. Prepare for 6G by investing now in the foundational technologies that will enable the immersive experiences promised by a 6G-enabled cyber-physical continuum. For instance, consider investing in technologies like terahertz communications, advanced edge computing, integrated satellite networks, and advanced materials.

4. Create domestic internship and apprenticeship programs to build talent pipelines in semiconductor and quantum skills, where shortages loom due to onshoring. Partner with schools to develop a homegrown workforce proficient in these technologies vital for national strategic interests.

5. Diversify sourcing of critical components to reduce overreliance and risk from any single country or region, and improve resilience. Build relationships with multiple suppliers and partners to mitigate concentration and gain flexibility to adapt to changing political and market conditions.

6. Fund research on organoid intelligence and neuromorphic computing, enabling collaborations to translate findings into commercial technologies. Partner with academia and startups on initiatives like brain-inspired chips and synthetic neural tissues to drive innovation in human-like cognition for applications from health care to robotics.

CENTRAL THEMES

AI-Driven Design

As AI's computational demands grow, traditional architectures are falling short, paving the way for alternatives like photonic and neuromorphic computing. Photonic computing leverages light's speed for faster and energy-efficient computations, providing a parallelism suitable for AI's requirements. Neuromorphic computing, mimicking the brain's structure, merges memory and processing, drastically reducing data fetch times for AI tasks. We aren't just reevaluating the architectures themselves—we are reevaluating how we even think about the architecture. And it may be the case that we aren't the best candidates for the job. The best candidate for designing an architecture suited to AI just might be AI. It's aiding in optimizing transistor placement, addressing cost, speed, and power efficiency issues. AI's impact is thus two-fold; it's driving the demand for advanced computation and also contributing to its design.

Protectionist Policies, Attitudes

The 2022 Chips Act provides roughly $280 billion to boost domestic research and manufacturing of semiconductors in the US, aiming to make the country less vulnerable to disruptions in the supply chain by bringing semiconductor fabrication plants in-house. We're now seeing similar protectionist attitudes emerge in other strategic technology areas like quantum computing and the technology that will eventually enable 6G. However, despite subsidies, this shift may still increase US production costs compared to countries like Taiwan, pressuring chip producers. It could also trigger talent shortages in relevant skills. While the goal is technological independence, these protectionist strategies may have implications on cost, talent acquisition, and global cooperation in key tech sectors. Pursuing self-reliance has trade-offs.

Computing Gets More Personal

Computers are becoming deeply integrated with us, redefining the "personal" in personal computing. Devices such as MIT Media Lab's AttentivU glasses enable us to control robots like Boston Dynamics' Spot with our eyes, while spray-on meshes developed by Seoul National University and Stanford University enable AI to interpret our hand gestures. Everyday objects are transforming into interactive interfaces, and as tech advances, our devices comprehend us more intimately. We're becoming interfaces for devices, which are morphing into extensions of us. Screens are moving closer to our faces via glasses and AR/VR headsets, while our brains can control artificial limbs, exemplifying this profound integration. Even our own skin can be an interactive interface, as seen with Cornell University's SkinPaper, which facilitates on-skin interactions for a range of applications, from art to health care.

CENTRAL THEMES

Accelerating Growth Through Open Source

Open-source software is spreading into new domains previously dominated by proprietary solutions. One example is in quantum computing, where the high costs of proprietary hardware and software has made quantum experimentation inaccessible for most researchers. Open-source quantum software toolkits like Qiskit and SuperConga are changing this by providing free access to simulate quantum circuits and materials. This allows a broader community to collaborate and drive innovation in quantum computing. Similarly, open-source chip architectures like RISC-V are transforming the semiconductor industry. Traditionally, companies like Intel and Arm have controlled chip design and manufacturing, but RISC-V makes instruction set architectures freely available for anyone to build custom chips. By opening access, open source allows more minds to tackle complex problems together, leading to advancements in fields that were previously dominated by closed, proprietary systems.

Abstraction: Layers on Layers

As computing grows more complex, new abstraction layers emerge to simplify access. In quantum computing, companies like Horizon Quantum Computing compile classical code so developers can program without grasping quantum mechanics. Quantum-as-a-service similarly insulates users from hardware intricacies. Conventional computing exhibits similar abstraction layers upon layers. Early cloud computing abstracted physical servers, enabling users to focus on applications without infrastructure concerns. Now "supercloud" layers integrate disparate cloud platforms, further simplifying management and cross-ecosystem operations. These abstraction layers divorce users from technical complexities, dramatically streamlining processes. Developers avoid wrestling with infrastructure intricacies, innovating instead at higher levels. Users interact with user-friendly interfaces rather than deal with technical details.

Researchers Take on Noise

Quantum computers face significant reliability challenges due to noise and errors that introduce inaccuracies during computations. "Quantum noise" refers to the inherent fluctuations and uncertainties that arise in quantum systems due to the principles of quantum mechanics. Researchers are pursuing various strategies to mitigate these issues. Noise reduction techniques aim to isolate qubits from environmental disturbances that cause errors. Other approaches focus on modeling the impact of noise to estimate and subtract out its effects after computations finish. There are also efforts to optimize qubit connectivity to reduce noise. Progress is happening, but substantially reducing errors remains an ongoing challenge. The inherently probabilistic nature of quantum physics means some baseline of noise will likely persist. However, researchers are encouraged by experimental demonstrations showing meaningful computations are possible even on today's error-prone hardware. Continued incremental advances in mitigating noise will help make quantum computers more robust and capable. Despite remaining limitations, researchers in this field are optimistic about eventually achieving practical applications.

ONES TO WATCH

Alireza Marandi, assistant professor of electrical engineering and applied physics at California Institute of Technology, for research on photonic cellular automata.

Alon Loeffler, synthetic biological intelligence postdoctoral scientist at the University of Sydney, for demonstrating nanowire networks can exhibit both short- and long-term memory like the human brain.

Ben Lanyon, physicist in the Department of Experimental Physics at the University of Innsbruck, for his work on the first long-distance quantum repeater node for telecommunication networks.

Brian Johnson, postdoctoral researcher at University of Colorado Boulder, for developing new soft actuators, sensors, and control algorithms for intelligent robotic materials.

Christina Tringides, postdoctoral fellow at ETH Zürich, for research on hydrogel scaffolds for neural cell differentiation.

Cindy Hsin-Liu Kao, assistant professor and director of the Hybrid Body Lab at Cornell, for work on wearable and ubiquitous computing, particularly on-skin interfaces.

Dirk Grundler, head of the Lab of Nanoscale Magnetic Materials and Magnonics in the School of Engineering at the Swiss Federal Institute of Technology, Lausanne, for research on magnon-based computation.

Brad Aimone, a Distinguished Member of Technical Staff in the Center for Computing Research at Sandia National Laboratories, for research on neuromorphic computing.

Chueh Loo Poh, principal investigator and professor at the College of Design and Engineering at the National University of Singapore, and the NUS Synthetic Biology for Clinical and Technological Innovation, for work on developing a biological camera that captures and stores images directly into DNA.

Hussam Amrouch, professor of AI processor design at the Technical University of Munich, for work on energy-saving AI chips.

Sanghyo Lee, senior research associate at University of Cambridge, for work on development of next-generation smart textiles.

Gordon H.Y. Li, graduate student at California Institute of Technology, for research on photonic cellular automata.

Jonathan Xu, researcher at Stanford and the National University of Singapore, for his work on brain image reconstruction using fMRI.

Mikael Fogelström, professor of theoretical physics at Chalmers, for his work on SuperConga, an open-source framework for mesoscopic superconductivity.

Nataliya Kos'myna, research scientist at MIT, for work on brain computer interface systems and research on fluid interfaces.

Pat Pataranutaporn, research assistant at MIT, for his research on synthetic virtual humans and synthetic biology, specifically at the interface between biological and digital systems.

Patric Holmvall, postdoctoral researcher in condensed matter physics at Uppsala University, for work on developing open-source, freely available software to speed quantum research.

Sajant Anand, Ph.D. candidate at University of California, Berkeley, for research on tensor network algorithms for simulation of quantum many-body systems on both classical and quantum computing.

Sunil Pai, quantum architect at PsiQuantum, for research that demonstrates in situ backpropagation can train photonic neural networks to solve a task.

Thomas Hartung, professor at Johns Hopkins, for his work to develop a collaborative, multidisciplinary program that aims to establish organoid intelligence as a genuine form of biological computing.

Vasha DuTell, postdoctoral fellow at MIT, for her work on perceptual straightness in computer vision.

Yasha Iravantchi, doctoral candidate at University of Michigan EECS, for work on developing novel sensing hardware, particularly SAWSense.

Youngseok Kim and **Andrew Eddins,** research scientists with IBM Quantum, for their 2023 paper "Evidence for the Use of Quantum Computing Before Fault Tolerance."

Bradley Theilman, a postdoctoral appointee at Sandia National Laboratories, for research on neuromorphic computing.

IMPORTANT TERMS

Biocomputer
A computer that uses biological molecules like DNA and cells to store and process information.

Brain-computer interface (BCI)
A direct interface between the brain and computer that can enable control and communication by thought alone, with potential to help people with disabilities as well as elucidate cognition.

Cellular automata
Computational models that evolve in discrete space and time according to simple rules based on local neighbor interactions.

Central processing unit (CPU)
The key computer component that performs the computations, makes decisions on data, and tells the other components what to do. You can think of it as the computer's mission control center.

Classical computer
The standard binary digital computer that manipulates zeros and ones to store data and perform computations sequentially using hardware chips and switches.

Exascale computers
Supercomputers capable of performing over 1 exaFLOPS, which is a quintillion calculations per second.

Fault tolerance
The ability of a quantum system to operate reliably despite errors and noise.

Form factor
The overall physical attributes and dimensions of a device according to standard specifications or for particular use cases. It impacts the usability and compatibility of hardware.

Graphics processing unit (GPU)
A specialized circuit designed to rapidly process and manipulate computer graphics and image data.

Hybrid classical-quantum
A computational architecture that combines both classical computers and quantum computers to exploit the complementary strengths of each.

Machine learning
A subfield of artificial intelligence that trains algorithms to learn from data, identify patterns, and make predictions or decisions without being explicitly programmed.

Magnonics
Aims to develop devices and circuits that use magnons for information processing and transmission.

Moore's law
The observation made by Intel co-founder Gordon Moore in 1965 that the number of transistors on an integrated circuit doubles about every two years. Recent challenges suggest Moore's law is approaching fundamental limits due to physics and cost.

Nanowire networks
Meshes or arrays of nanoscale wires used to build devices and circuits. They can exhibit unique optical, electrical, thermal, and chemical characteristics.

Neuromorphic computing
Computer architectures that are inspired by the biological brain's structure and function.

Open source
Computer software or other products with source code that anyone can inspect, modify, and enhance.

Organoid intelligence
A new scientific field of study that aims to actualize biological computing by utilizing 3D cultures of human brain cells and brain-machine interfaces.

Parallel spatial computing
Computer architectures optimized to perform many operations simultaneously across a large grid or array of simple spatial processing elements.

Perceptual straightness
The ability to perceive dynamic visual information and transform it into a stable mental representation.

Pervasive (ubiquitous) computing
Aims to seamlessly integrate computer hardware and software into all objects and activities, creating an always available, helpful computing environment.

Photonic chips
Integrated circuits that generate, manipulate, and detect light waves and photons to process information.

Q-Day
The hypothetical point in the future when a fully operational quantum computer capable of running practical quantum algorithms finally becomes available.

Quantum advantage
Also known as quantum supremacy, refers to the potential capability of quantum computers to solve

IMPORTANT TERMS

certain problems that are intractable for classical computers in practical timeframes.

Quantum-as-a-service
The provision of quantum computing resources on demand as a cloud service.

Quantum circuit model
The most common model for quantum programming and computation. One key aspect is that programs are expressed as circuits consisting of qubits and quantum gates operating on the qubits. The circuit model provides a simple abstraction to reason about quantum programs.

Quantum computer
A type of computer that utilizes quantum mechanical phenomena like superposition and entanglement to perform computations. Unlike classical computers which operate on binary bits (0 or 1), quantum bits, or qubits, these computers can represent a 0, 1, or a quantum superposition of both states at the same time. Since they consider multiple possibilities simultaneously, they can potentially be vastly faster at some types of problems than classical computers.

Quantum entanglement
A phenomenon in which two or more quantum particles are intrinsically linked to each other in such a way that the state of one particle cannot be described independently of the others, even when separated by a large distance.

Quantum internet
A hypothetical global quantum communication network that connects quantum processors using quantum entanglement and teleportation.

Quantum superposition
Allowing a quantum system to exist in multiple possible states at the same time until it is measured. The quantum parallel processing enabled by superposition is fundamental to achieving speedups and novel applications using quantum computers.

Qubit
The basic unit of information in quantum computing. Unlike classical bits, qubits can be in a superposition of 0 and 1 simultaneously. The superposition, entanglement, and interference properties of qubits are what allow quantum algorithms to efficiently solve certain problems that are believed to be intractable on classical computers.

RISC-V
An open-source instruction set architecture based on established reduced instruction set computer (RISC) principles.

RSA encryption
A public-key algorithm currently widely used for secure data transmission that will become insecure in the quantum era. RSA security depends on the difficulty of factoring large integers, which quantum computers will be able to efficiently solve.

Superconductor
A material that can conduct electricity with zero electrical resistance. This means that, unlike typical conductors, superconductors can carry an electrical current indefinitely without losing any energy to heat or electrical resistance.

CHIPS

CHIPS

Chip Onshoring

The CHIPS Act, signed into law in August 2022, has sparked numerous initiatives to bolster the US semiconductor industry. Over 50 new chip facility projects have been announced since the legislation was introduced, with private companies pledging over $210 billion in investments. Intel unveiled plans for a $20 billion chip fabrication complex outside Columbus, Ohio; Micron plans to invest up to $100 billion over the next 20-plus years; Samsung is exploring building 11 plants in Texas with one plant already costing the chipmaker $25 billion ($8 billion more than forecasted). General Motors announced an unprecedented, long-term partnership with GlobalFoundries, which will establish dedicated chip production capacity exclusively for GM in upstate New York. Taiwan Semiconductor Manufacturing Co. (TSMC), the world's largest advanced chip manufacturer, broke ground on a major facility in Phoenix and increased its investment to $40 billion. The aim of the onshoring efforts is to reduce US vulnerability to foreign disruptions. However, the US is making a trade-off with this approach; onshoring is often costlier. In a recent submission to the US Commerce Department, TSMC complained the Phoenix plant would cost substantially more than an equivalent facility in Taiwan, citing higher wages and taxes, lower productivity, a greater likelihood of delays, and more stringent regulations.

These onshoring initiatives coincide with a tightening of tech export controls to China. In March 2023, NVIDIA introduced the H800 chip, compliant with Commerce Department guidelines and a substitute for the restricted H100 chips in China. October 2023 saw new restrictions halting China-specific A800 and H800 exports, disrupting NVIDIA's plans to fulfill additional orders. This shift forced China to turn to non-US chip suppliers, resulting in companies like Baidu, a long-term NVIDIA client, opting for Huawei's AI chips instead.

Chip Talent Shortage

The global semiconductor industry is grappling with a shortage of skilled talent. According to some estimates, the US will face a deficit of 70,000 to 90,000 workers over the next few years, ballooning to a shortfall of 300,000 engineers and 90,000 technicians by 2030. Due to a shortage of skilled labor, TSMC has reported new delays in the progress of its $40 billion Arizona facility. The skills gap extends beyond America's borders. Taiwan, a leader in cutting-edge chipmaking, faced a shortage of over 30,000 workers at the end of 2021, up 77% from 2020. China's massive semiconductor industry is wrestling with a shortfall of 300,000 skilled workers. South Korea expects at least 30,000 fewer skilled workers than required over the next decade as universities produce less than half the number of graduates needed. In Japan, major manufacturers warn that the industry's revival is in jeopardy without 35,000 additional engineers. European semiconductor growth is also hampered by a substantial talent deficit, industry leaders say. The push to reshore semiconductor manufacturing has put the unintended consequences into sharp focus. While bringing chip production back to America could bolster supply chain security, developing talent will take time.

The booming US semiconductor sector faces a shortage of skilled chip fabrication skills, raising concerns that a lack of qualified talent could jeopardize billions invested in expanding domestic chip manufacturing.

CHIPS

Chips to Optimize AI Workload

Embedding advanced AI comes at a computational cost. For instance, researchers estimated that for Google to add GPT-3 into every search query, it would need 2.7 billion of NVIDIA's old A100 chips, which would cost more than $40 billion. This staggering price tag highlights the demand for more efficient AI chips to make AI scalable and accessible. NVIDIA responded with the H100 chip, optimized for generative AI and named after pioneer Grace Hopper. With substantially faster processing than previous chips, the H100 is crucial for companies seeking to develop AI services. In November 2023, NVIDIA escalated its AI computing power further with the NVIDIA HGXTM H200, building on the HopperTM architecture. As the first GPU with HBM3e memory, the H200 enables faster processing essential for generative AI and large language models, while boosting scientific computing. Compared to the A100, it delivers double the memory capacity and 2.4 times more bandwidth. In a parallel development, Amazon Web Services (AWS) announced Trainium2, engineered specifically for training AI models. Moreover, AWS plans to provide access to NVIDIA's next-generation H200 GPUs through a specialized computing cluster, accessible to both AWS customers and NVIDIA. To reduce dependence on Nvidia, Microsoft has developed its proprietary AI chip designed for training LLMs. Additionally, the company has created its own ARM-based CPU tailored for cloud workloads. These chips will be used to power Azure data centers for their AI-hungry customers.

Researchers are also advancing AI chip architecture in ways that could shape the next generation. For example, one computer scientist developed an in-memory computing chip that processes and stores data directly within each transistor, taking inspiration from the human brain's ability to simultaneously process signals and store information. This chip delivers twice the power efficiency of alternatives.

Photonic Chips

With the continued growth of AI models, energy consumption also escalates. This is where photonic AI chips, which operate using light rather than electricity, show promise in improving efficiency. They are more energy efficient than alternatives because they excel at performing matrix multiplications, a fundamental operation in deep learning models. But until now, the application of photonic AI chips was limited to inference tasks, as they struggled with implementing the vital algorithm required to train neural networks, known as backpropagation.

A team at Stanford has overcome this challenge by successfully training AI on an optical chip, a first in the field. Their photonic chip allows light signals to pass in both directions through an optical neural network, and it has built-in light detectors to measure the intensity of light passing through each component. This enables the chip to optically implement backpropagation. As a result, the researchers were able to train a simple neural network to label data points with up to 98% accuracy. While there is still room for improvement, this milestone demonstrates the potential of photonic processors to increase the energy efficiency of AI.

RISC-V

RISC-V, an open-source computer chip architecture, is disrupting the semiconductor industry. Traditionally, companies like Intel designed proprietary chip blueprints and sold pre-made chips to customers. Conversely, RISC-V specifications are free for anyone to use to design chips. RISC-V defines the basic functions, known as the instruction set, that a chip can perform to manipulate the values of transistors—for adding numbers, for example. Around 3,100 members, including companies and universities worldwide, collaborate through the nonprofit RISC-V International to develop these specifications. Intel announced a $1 billion fund to support companies building RISC-V chips, and Google wants RISC-V to become a “tier-1” Android architecture.

Worldwide, events like the global chip shortage and Arm's corporate instability are fueling interest in RISC-V. In China, an added urgency is driving RISC-V's adoption. The country wants to reduce reliance on foreign intellectual property and achieve self-sufficiency in chip design, particularly in light of US trade

CHIPS

restrictions on advanced integrated circuit technologies. Consequently, many Chinese companies that design computer chips but don't make them are considering a switch to RISC-V, which is becoming an increasingly attractive option in the region. In late 2023, the House Select Committee on the Chinese Communist Party suggested the formation of an interagency governmental committee to assess the potential risks associated with RISC-V. This recommendation stems from concerns that the open-source, easily accessible nature of RISC-V might weaken US export control efforts.

AI-Driven Chip Design

Major tech companies like NVIDIA are using AI to improve AI chip design. Designing chips involves placing billions of transistors, and their placement has an enormous impact on cost, speed, and power efficiency. In March 2023, NVIDIA released a paper building on existing research from Alphabet, showing that a combination of AI techniques can find more optimal ways to place large groups of transistors. As per-transistor costs increase with each new generation of chip manufacturing technology (contrary to Moore's law), NVIDIA chief scientist Bill Dally emphasizes the need for more intelligent design instead of relying on cheaper transistors.

Besides NVIDIA, other major players in the industry are also recognizing the benefits of integrating AI into their chip design processes. For instance, Synopsys and Cadence Design Systems are in a race to provide AI-infused software that companies can use to create their own optimized chips. The integration of AI will help engineers boost the proportion of defect-free chips coming off the production line. Synopsys CEO Aart de Geus said the company intends to invest more in AI tools, especially as the semiconductor industry transitions to chiplets—multiple chips stacked and integrated together to create larger, more complex chips. With major players ramping up AI adoption, the semiconductor industry is poised to benefit from smarter, more automated design.

Custom AI Chips

Instead of relying on traditional chip suppliers like Intel, major tech companies like Meta, Google, and Microsoft are developing their own AI chips and hardware to improve the efficiency, cost, and performance of running AI models. Meta's AI chip is currently focused on inference, not training; the project signals the company's ambition to catch up to rivals in custom AI hardware after previously relying on off-the-shelf CPUs, GPUs, and costly data center redesigns. Microsoft is also reportedly developing its own AI chips to train large language models, reducing reliance on costly NVIDIA GPUs. Microsoft aims to cut costs with these in-house chips; they may be available internally and for OpenAI next year, with future generations planned. The chips won't directly replace NVIDIA but could lower Microsoft's AI costs as the company expands AI in Bing, Office, GitHub, and more.

ARM-based PC Chips

For decades, the personal computing market has run on x86 chips from the likes of Intel and Qualcomm. But ARM architecture, renowned for power efficiency, is staging a takeover. ARM already dominates mobile. Now major players are bringing ARM to PCs, challenging the x86 foothold. NVIDIA and AMD are making strategic moves by adopting ARM's technology. NVIDIA is venturing into the central processing unit (CPU) arena for personal computers with ARM-based designs. These CPUs, compatible with Microsoft Corp.'s Windows operating system, are anticipated to be available as early as 2025. Similarly, AMD is also reported to be developing ARM-based CPUs for Windows PCs, marking a significant diversification from their traditional product offerings. Microsoft announced plans in November 2023 to roll out its own ARM-based CPU, expected to happen sometime in 2024. The entry of NVIDIA and AMD into the ARM-based PC market poses a new challenge to Intel and Qualcomm. Intel, in particular, faces increased competition at a time when it is striving to reclaim its market share and technological edge. With AMD and NVIDIA joining the ranks of Apple and potentially Microsoft in adopting ARM's architecture, the pressure is mounting on Intel to innovate and compete.

CHIPS

Manufacturing Intelligence

To tap into AI's potential, leading companies like Foxconn and NVIDIA are collaborating to build a new generation of data centers purpose-built for AI workloads. Dubbed "AI factories", these state-of-the-art data centers packed with NVIDIA's latest chips, enterprise software, and other hardware will fuel a wave of AI innovation. Foxconn plans to leverage them to digitize inspections, develop smarter robotics and vehicles, power generative AI applications, and more. The scale of data and model training needed for industrial AI adoption requires specialized infrastructure. While AI chips continue advancing, massive computational horsepower is still essential. Dedicated AI data centers like Foxconn and NVIDIA's can crunch vast datasets into valuable AI assets far faster than typical facilities. Looking ahead, we can anticipate a trend where more data centers will tailor their services to accommodate these demanding AI workloads. Such specialized data centers could emerge as a distinctive offering in the market, characterized by their focus on AI-specific computing resources. This shift signifies a pivotal moment in the evolution of data centers, aligning them more closely with the rapidly advancing realm of artificial intelligence.

AI factories will offer the vast computational power and customized infrastructure essential for enabling widespread AI adoption.

PERSONAL COMPUTING

PERSONAL COMPUTING

Everywhere Input

Researchers at the University of Michigan have developed a system that can turn everyday surfaces into high-accuracy input devices. Named SAWsense after the "surface acoustic waves" it utilizes, the system employs acoustic sensors to transform everyday objects like couches, tables, and sleeves that respond to commands in the form of taps, scratches, and swipes. Imagine sitting on your living room couch, watching a movie on your smart TV. Instead of reaching for a remote control, you merely tap twice on the armrest of your couch, and the movie pauses. The system works on materials like wood, metal, and fabric with 97% accuracy. These new forms of interaction with computers, through more integrated and personalized interfaces, signal the emergence of ubiquitous and ambient computing. Expanding this concept further, engineers from the University of Colorado Boulder envision a future with dynamic 3D interfaces. Imagine an iPad with a surface that enables you to draw 3D designs; the shape-shifting display uses a grid of soft robotic "muscles," called HASEL actuators. Each of these actuators is a miniature plastic pouch shaped like an accordion that expands to create patterns when electrified. The innovation is precise enough to generate scrolling text and even imitate physical sensation, providing a rare haptic touch to the digital world.

Smart Textiles

An international research team led by the University of Cambridge has developed next-generation smart textiles that are low-cost, sustainable, and produced using standard industrial looms. Unlike previous smart fabrics, these textiles can withstand bending and folding thanks to a process that coats conductive fibers with stretchable materials. The 46-inch woven prototype seamlessly integrates flexible embedded displays. The researchers envision the use of these flexible, eco-friendly smart textiles in various applications such as buildings, car interiors, and clothing. Separately, researchers developed a touch-responsive fabric armband that can act as a flexible keyboard and wearable sketchpad. It uses clear conductive hydrogel and graphene nanosheets between layers of silk fabric to sense touch in real time. The fabric has been demonstrated to control a computer game and sketch on a computer. The fabric innovations could help drive the widespread adoption of e-textiles and open new opportunities for wearables and smart devices. Scientists also developed the first smart fabric that changes both color and shape in response to temperature and electricity. Made of polymer nano-fibers from recycled plastic, this cost-effective material has extensive potential uses. It represents a milestone in creating practical, affordable smart textiles that can transform our everyday environments.

Human-Centric Pervasive Computing

Pervasive computing, also known as ubiquitous computing, embeds computational capabilities into ordinary objects and environments so that computing can become an invisible and seamless part of everyday life. It's even being integrated onto skin—researchers at Cornell University have developed technologies that allow users to

Pervasive computing will enable people to interact with computers without screens.

PERSONAL COMPUTING

easily construct and use customized on-skin devices for sensing and display. One device, called SkinPaper, uses silicone-treated washi paper that conforms to the body to enable simple on-skin interactions; it could eventually enable a range of promising applications, from health monitoring and personal safety to assistive technologies for the disabled. Another team from Seoul National University and Stanford University developed a spray-on smart skin that uses AI to recognize hand gestures and typing. This spray-on mesh is made of nanowires embedded in a polyurethane coating, and is applied directly to the skin, conforming to its wrinkles and folds. This smart skin allows for seamless gesture recognition without cameras, gloves, or virtual reality systems; it could enable new ways for people to communicate with each other and control devices.

Microsoft researchers are also experimenting with new ways for people to communicate with each other and control devices using our tongues. By combining tongue gestures with gaze, selections occurred faster than just using gaze alone. The researchers have found that the tongue-gaze method can be used as a nonintrusive point-and-click interface.

Wearable AI

AI is changing human-computer interaction, shifting us away from screens, trackpads, and keyboards towards more intuitive, voice-based interfaces. This is giving rise to a new class of lightweight, wearable gadgets and screenless computers that integrate seamlessly into daily life. By reducing screen fatigue and intrusive features, these devices foster a more natural, human-centric approach to technology. A prime example is the newly-launched Humane AI Pin, an OpenAI-powered wearable priced at $699, plus a $24 monthly subscription. Forgoing traditional app interfaces, this 34-gram device focuses solely on voice interactions. Users access information and perform tasks by speaking to the Pin's built-in microphone. By stripping down the technological interface, Humane aims to create a streamlined, human-like experience. Another device is the Rewind AI Pendant which captures real-world

As AI enables more natural computer interaction, there are increasing use cases for compact, perhaps screenless wearables.

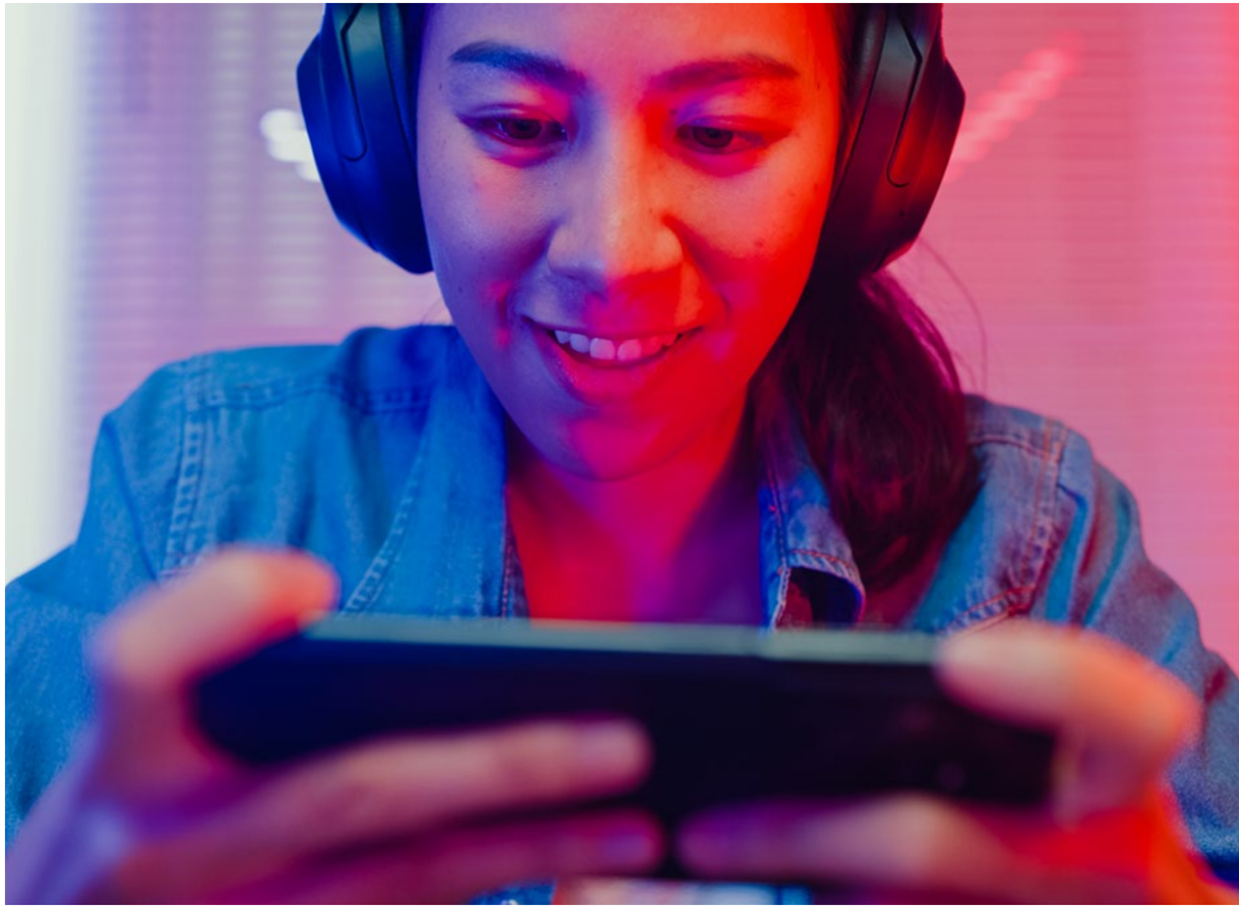
PERSONAL COMPUTING

conversations, storing encrypted transcripts and audio locally on the user's phone. Beyond recording, Rewind's platform searches transcripts, generates meeting summaries and analyzes speech patterns. Essentially, the Pendant serves as a personalized assistant harnessing environmental information to support the user. Both the Humane Pin and Rewind Pendant epitomize the shift towards invisible, assistive technology that facilitates life's tasks and interactions much like a helpful human companion would. This evolution in form and function represents a paradigm shift, integrating technology more seamlessly while making it feel more intuitive and human-centric.

The Convergence of Gaming Devices for Productivity

The portable PC market is gaining momentum, fueled in part by interest in dedicated gaming devices. While many portable PCs were initially targeted at gamers seeking power and performance on the go, they show potential for other applications. This potential is reflected in a leaked video showing Microsoft exploring an optimized "Windows handheld mode" for gaming devices like the Steam Deck. The video shows a prototype with a custom game launcher, controller-friendly keyboard, and floating taskbar designed for touchscreens. If developed further, this could enable handheld PCs to run Windows and games from multiple stores.

Going in the opposite direction, a developer separately created a way to use Steam Deck controls in Windows, suggesting the gaming-centric design could suit more general purposes. Though preliminary, these signs indicate the promise of handheld PCs for both gaming and productivity. They could serve enterprise and business users as ultralight yet high-performance secondary machines or bring-your-own-device options. Their versatility, comfort with both touch and keyboard input, and suitability for entertainment and productivity make them an intriguing form factor for multiple use cases.



Handheld gaming devices pack impressive computing power that could be utilized for AI-assisted productivity tools.

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Silent Signals

A dense forest in a hostile territory: Night has fallen, and visibility is limited. A special forces team is tasked with rescuing hostages from a heavily guarded compound. Their mission depends on stealth and silent communication, which is why they're equipped with the latest spray-on smart skin technology.

The team gathers at a concealed location near the target and applies the smart skin mesh to each team member's hands. They will use hand gestures to communicate with each other and the remote tactical operations center.

They move silently toward the compound. The team leader raises his hand in the "hold" signal, and the team freezes. Using more hand gestures, he conveys there are enemy guards nearby. That gesture data also makes the tactical operations center immediately aware of the team's status—without any verbal communication or interceptable radio communications that would give away their location.

The team leader signals that he needs feedback from the overhead drone to check movement out of his line of sight. He receives silent haptic feedback in his gloves; the staccato pulse vibrations confirm that there is movement, and the opposing forces know the soldiers are there. He signals to his team to execute plan B. The element of surprise is lost but the technological advantage remains.

The primary benefit of this technology lies in enabling communication where radio transmissions and verbal commands might otherwise betray position. These silent gestures serve not only for on-the-ground communication between team members but also facilitate remote interaction with tactical operations, providing a discreet and untraceable channel for vital information exchange.

PERSONAL COMPUTING

Right to Repair

The Right to Repair movement has rapidly gained momentum across the United States, with several states passing laws to empower consumers and independent repair shops in the face of repair restrictions imposed by manufacturers. This addresses growing concerns that companies severely limit access to replacement parts, tools, and service information for items like electronics and machinery, forcing reliance on often costlier authorized service providers. California is the latest state to enact Right to Repair legislation, following New York, Colorado and Minnesota over the last year. The bill guarantees consumer access to the components, manuals and diagnostic software needed to service and repair electronic products. Significantly, Apple expressed support for the law despite past lobbying efforts against repair reforms. This shift came amidst criticism of Apple for utilizing software locks that prevent functioning hardware from operating fully unless repaired by Apple technicians using strictly Apple components.

However, challenges linger regarding adherence to the spirit of the laws. For example, Apple's recent iPhone 15 contains proprietary software locks that inhibit non-Apple replacements, triggering warning messages or disabled features. Repair authority iFixit.com has highlighted how these exclusive locks undermine Right to Repair progress by limiting choice and affordability around genuine repairs.

Maximum Cooling to Minimize PC Size

There are traditionally two cooling methods for PCs: active cooling with fans and passive cooling without fans. A startup called Frore Systems has developed a novel third method: an innovative solid-state device called AirJet that provides active cooling in a quieter and more compact form factor. AirJet's vibrating membranes in the chip create suction and push high-velocity air to cool the copper heat spreader below the chip. Frore Systems found PCs equipped with AirJet performed better than those without while running intensive graphics stress tests: 9-11 frames per second compared with barely one frame per second. Because adding more AirJets doesn't make the device thicker or noisier, in the future PCs equipped with the technology could be quieter, thinner and have bigger batteries. The company sees potential for AirJet in gaming smartphones, 4K webcams, stick PCs, storage devices, doorbell cameras, and LED light bulbs.

LLMS as Operating Systems

In November 2023, AI luminary Andrej Karpathy introduced a groundbreaking concept that could redefine our interaction with computers: an operating system fundamentally powered by a LLM. The LLM would not just be an add-on feature; the LLM would function as the core kernel of the OS. Routine tasks could be executed with an unprecedented level of sophistication, automating operations that once required manual intervention. The user interface in this envisioned OS departs from traditional graphical user interfaces (GUIs) and command-line interactions. It embraces a more intuitive, natural language–based interface. Users can interact with their computers through conversa-

The right to repair advocates for allowing customers and independent shops to fix their own devices independently of the original manufacturer.

PERSONAL COMPUTING

tional commands, inquiries, or requests for specific tasks. The LLM, understanding these requests, would perform a series of actions to accomplish the desired outcomes. This concept has moved beyond theory into practical application, as demonstrated by Jesse Lyu, CEO and founder of Rabbit. Lyu launched the R1, a compact device about half the size of an iPhone, running on Rabbit OS—an operating system grounded in a LLM. Rabbit OS functions as a universal app controller, akin to systems like Alexa or Google Assistant, yet it offers a unique twist. It simplifies user interaction by removing the need to navigate through multiple apps or perform repetitive logins. Instead, users can directly communicate their needs to the device, and R1, understanding these natural language requests, efficiently executes the desired tasks.

Personal Computers on Wheels

Major automakers are transforming their cars into personal computers on wheels. Intel recently introduced a new AI-enhanced system-on-a-chip specifically for cars, with Zeekr being the first to implement this technology.

Intel's move into the automotive sector is marked by the introduction of the "first-generation AI-enhanced software-defined vehicle system-on-chip." This development is part of its broader strategy to integrate AI across various platforms, emphasizing the importance of personal computing devices, including cars, as secure environments for AI processing compared to cloud-based solutions. Volkswagen is another example, showcasing its integration of the AI-based ChatGPT in its IDA voice assistant in vehicles. Volkswagen plans to standardize this feature in many of its production vehicles in 2024, being the first volume manufacturer to do so. BMW is also reimagining the in-car experience. The company is enhancing its vehicles with streaming video, gaming options, and augmented reality, powered by AI-driven voice assistants, using Amazon's Alexa technology as a base. This assistant is designed to interact in a more human-like, conversational manner, offering both information about vehicle functions and control over some of these functions.

These advancements signal a paradigm shift in vehicle interfaces, aligning them more closely with digital lifestyles. As people grow accustomed to constant access to entertainment and information, car manufacturers are acknowledging the transformation of cars into multifunctional personal devices. These vehicles are now platforms for productivity, social connectivity, and leisure, marking a pivotal evolution in the automotive industry and fundamentally changing how we interact with our vehicles.

Since AI enables natural language input, we can now communicate more effectively with computers in vehicles, making personal computing accessible wherever we choose, including in our cars.

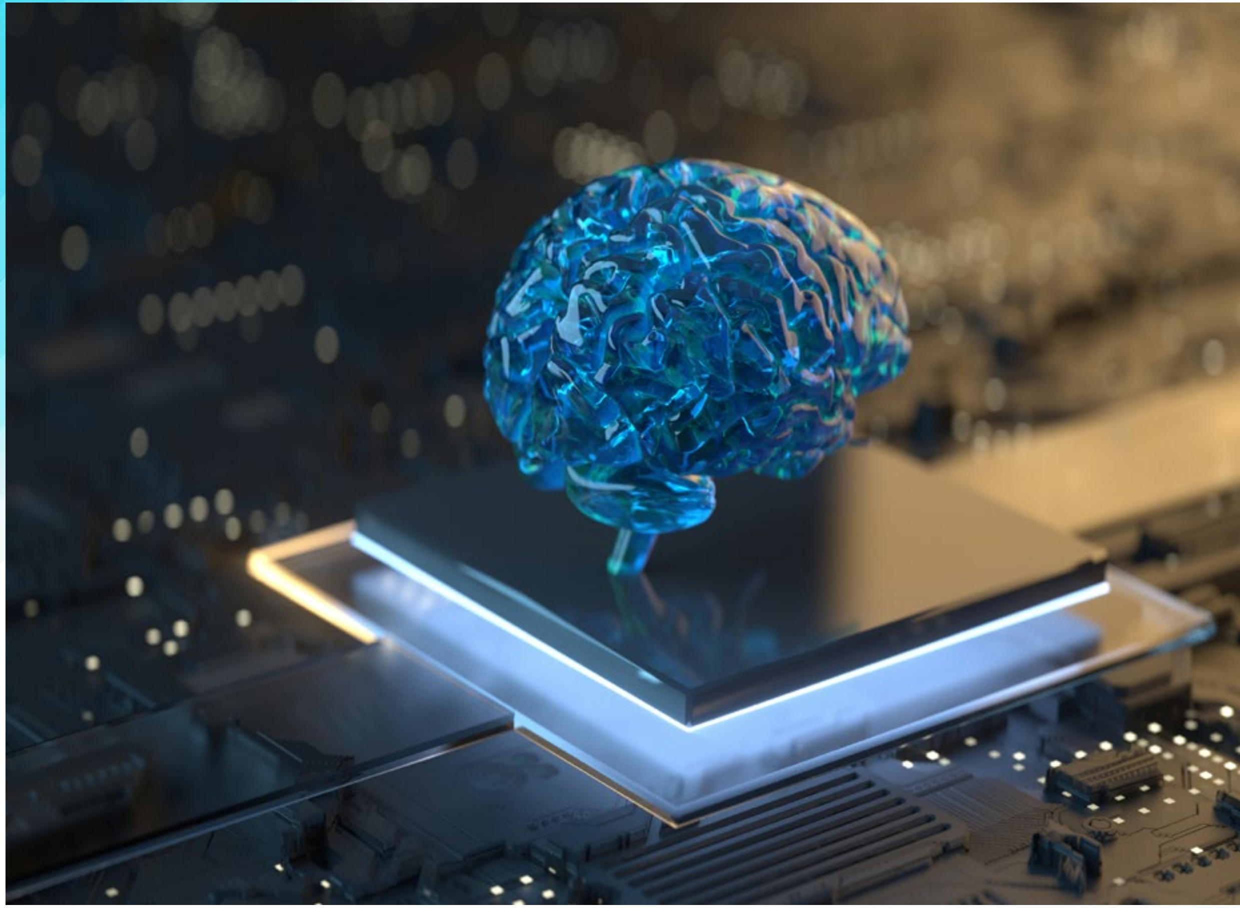
BIOLOGICAL COMPUTING

BIOLOGICAL COMPUTING

Neuromorphic Computing

Researchers are experimenting with new architectures to make computers faster and more energy efficient. One such approach is neuromorphic computing, which is inspired by the most energy-efficient computer on earth: our human brains. Where conventional computers must run commands sequentially, laboriously moving data back and forth between the memory and processor, neuromorphic chips simultaneously store and process information. Intel's neuromorphic chips have already achieved up to 1,000 times higher energy efficiency compared to general-purpose chips and excel at detecting sensory input like gestures, sounds, and even smells. These chips have enabled a variety of systems, from artificial skin that can sense touch to an "electronic nose" capable of identifying scents from explosives. Other large-scale neuromorphic architecture projects include IBM's TrueNorth, SpiNNaker, BrainScaleS, and Tianjic.

While neuromorphic computers have not yet replaced conventional hardware, recent research shows promise. For instance, researchers at Sandia National Laboratories have demonstrated that approximation algorithms can be implemented on neuromorphic hardware to efficiently solve complex optimization problems. Separately, a joint team from Purdue, USCD, and ESPCI is working on research that underscores the need for materials vastly different from silicon, which can naturally replicate synapses and neurons. The team's breakthrough involves using vanadium dioxide, a material exhibiting both synaptic and neuristor capabilities. They've discovered a way to visually monitor changes within this material, revealing that memory accumulates across the entire sample. This insight opens up new possibilities on how and where to control this property, potentially enhancing the synaptic behavior of neuromorphic materials.



Neuromorphic computing mimics the neural structure and processing method of the human brain to create more efficient computer systems.

BIOLOGICAL COMPUTING

Organoid Intelligence

The key distinction between biocomputers and neuromorphic computing resides in the systems and elements they each seek to replicate and harness. Neuromorphic computing aims to mirror its efficiency in the design of computing systems while biocomputing looks to utilize the inherent capabilities of biological materials or systems for information processing.

Researchers at Johns Hopkins University recently outlined a vision for the future of biocomputers, powered by human brain cells, in a paper published in the journal Frontiers in Science. Led by Thomas Hartung, the team outlined a roadmap for "organoid intelligence," aiming to bring biological computing to life using 3D cultures of human brain cells. These tiny 3D organoids, no larger than the point of a pen, are equipped with neurons and circuitry capable of supporting fundamental functions such as learning and memory. Organoid intelligence holds significant potential for augmenting computing capabilities while concurrently addressing the escalating energy consumption demands driven by advancements in artificial intelligence and supercomputing. Despite traditional computers' ability to process calculations at speeds far surpassing human capabilities, human brains demonstrate superior performance in complex decision-making tasks, such as differentiating between a dog and a cat. Running AI on organoids could be the key to achieving human-like complex decision-making.

Furthermore, running AI on organoids would be more energy efficient. As AI systems like self-driving cars become more complex, they will require massive amounts of computing power and energy; for instance, self-driving cars are estimated to use up to 20% more energy than conventional cars. In the next decade, computers utilizing biological hardware could begin to address the increasingly unsustainable energy consumption demands.

Living AIs Solve Equations

Indiana University researchers have crafted an organoid with lab-grown human brain cell clusters capable of solving elementary math tasks. Named Brainoware, this system harnesses living brain tissue for computations, potentially lowering the energy demands of sophisticated AI platforms. In initial tests, the brain organoids could solve a complex math problem called the Hénon map, demonstrating their ability to perform computations. While the organoids are limited in size due to a lack of blood vessels, the research shows promise for using living hardware to address the energy and hardware limitations faced by increasingly complex AI systems. It should be noted that the Brainoware research has been published on the preprint server bioRxiv, though not yet in a peer-reviewed journal.

BCI + Robots

MIT Media lab and Boston Dynamics are collaborating to build the first brain-controlled robot. The project, called Ddog, combines Boston Dynamics' Spot robot with an EEG brain-computer interface system called AttentivU that uses wireless glasses to measure brain activity and eye movements. These signals are then interpreted to control the Spot robot in real time. Ddog builds on an existing app called Brain Switch, which allows people with limited mobility to communicate nonverbally with the help of caregivers; it's completely wireless and autonomous, running on two iPhones without the need for electrodes or heavy computing equipment. Ddog conveys the promise of combining neurotechnology and robotics to empower users and assist them in meaningful ways, such as by deliver-

BIOLOGICAL COMPUTING

ing groceries or other objects, moving furniture, or retrieving items using Spot's robotic arm. Because the system is highly mobile and practical for in-home use, it has significant applications for less mobile populations, including those with disabilities and the elderly. As populations continue to age, human workers may not be able to provide assistance to all those who need it. Systems like Ddog show how robots can help fill in the gaps, providing autonomy and a better quality of life for users.

Soft Implantables

Conventional brain implants are rigid, making them ill-suited for the soft tissues of the brain. To address this, engineers at Rice University developed an alternative: ultraflexible nanoelectrodes that can achieve connections with minimal harm. These tiny, flexible implants deliver targeted electrical pulses that closely match natural neural signaling. With their precision and biocompatibility, the flexible nanoelectrodes could enable new therapies like sensory or motor prosthetics. Separately, Harvard researchers are developing a soft electrode using natural hydrogels extracted from seaweed. These gels possess the same pliability and responsiveness as the brain itself. Anchored to the organ's movements rather than resisting them, hydrogel electrodes could foster connections that stand the test of time. The researchers note that soft, biologically based electrodes may permit more natural cell contact and integration than their stiff, metallic counterparts.

Conventional implants have another limitation: they are temporary. As the soft brain moves, it repeatedly collides with rigid electrodes and gets damaged. In response, scar tissue builds up around the implant, cutting it off from surrounding neurons. Within a few years, this scarring isolates the device to the point that it must be replaced. Researchers at Linköping University developed a solution: Rather than building an electrode outside the brain and forcing it in, they designed an injectable gel. Once inside the brain, the gel solidifies into a conductive, yet pliable, electrode. Because this electrode moves with the brain, it avoids the damage that leads to scarring around the implant. The researchers' biomimetic approach, allowing the brain's own movements to shape the implant, holds promise for crafting neural interfaces that last as long as they are needed.

Nanowire Networks Emulate Our Memories

Researchers at the University of Sydney built nanowire networks that physically mimic the structure of the human brain. These networks—composed of mesh silver wires—exhibited both short-term and long-term memory, which suggests that brain-like learning and memory could potentially be replicated in non-biological systems. When information in the nanowire network is repeatedly reinforced, it becomes consolidated into long-term memory, similar to how our brains convert short-term memories into long-term memories. This research expands on previous work showing nanotechnology can be used to build brain-inspired devices with neural network-like circuits and synapse-like signaling; the results suggest the essence of human-level intelligence could arise from physical structures.

Imitating Human Perception: Advancing Computer Vision

Humans are good at predicting how objects and people will move. When we pass a person on the sidewalk, we have a good model of their trajectory; when we are stopped at a red light at an intersection, we can reasonably predict which oncoming cars will turn. This is because we exhibit "perceptual straightness"—the ability to perceive dynamic visual information and transform it into a stable mental representation. Unlike humans, computer vision models typically lack this ability, which is a problem if we want to interact with mobile robots or autonomous vehicles. But that could change, after MIT researchers identified a property that helps computer vision models learn to represent the visual world in a more stable, predictable way. The researchers found that training computer vision models using adversarial training, which makes them less sensitive to small errors in images, improves their perceptual straightness. They also found that the task a model is trained on affects its perceptual straightness: It's more effective to train models on abstract tasks like image

BIOLOGICAL COMPUTING

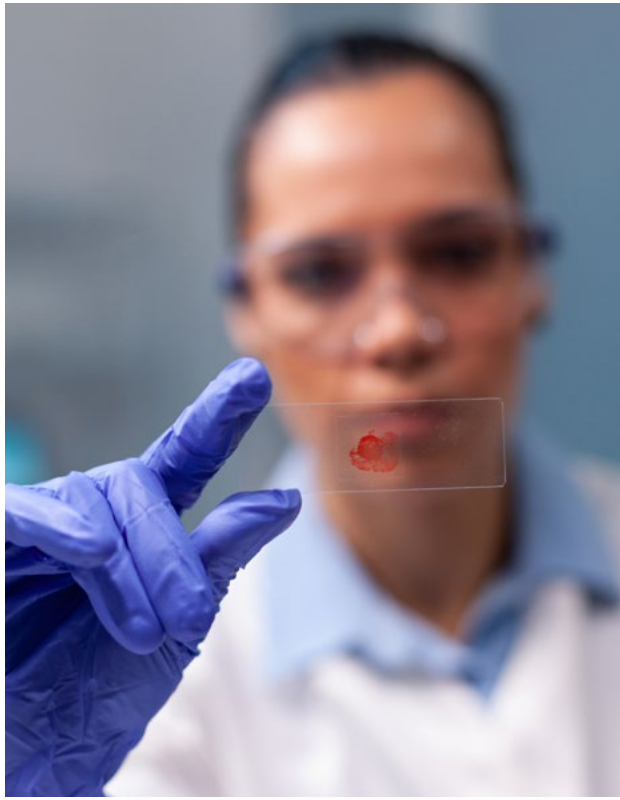
classification than fine-grained tasks like pixel-wise classification. Understanding perceptual straightness in computer vision could help make robot/human interaction safer since better computer vision would help robots better predict trajectories of people and vehicles.

Storing Images in DNA With Biological Camera

Researchers are exploring DNA computing as an alternative storage medium to resource-intensive data centers, due to DNA's immense storage capacity and long-term stability. However, current DNA storage research focuses on synthesizing DNA strands outside of cells, an expensive, complex, error-prone process. To overcome this challenge, researchers at the National University of Singapore turned to live cells containing DNA that act as a natural "data bank." The system—called BacCam—emulates a digital camera's functions using biological components. "Imagine the DNA within a cell as an undeveloped photographic film," explained associate professor Chueh Loo Poh, who led the research. "Using optogenetics—a technique that controls the activity of cells with light akin to the shutter mechanism of a camera, we managed to capture 'images' by imprinting light signals onto the DNA 'film.'" BacCam can capture and store multiple images simultaneously using different light colors, and the images were marked with barcoding for labeling purposes. Machine learning algorithms organized, sorted, and reconstructed the images, constituting a "biological camera" that mirrors a digital camera's data capture, storage, and retrieval capabilities. Importantly, compared to prior DNA storage methods, the team's innovative system is easily reproducible and scalable.

DNA-Based Molecular Computing

Traditional computer hardware is limited in its ability to interface with living organs, and computerized implants require a constant supply of electricity and cause damage to soft tissue. Researchers at the University of Minnesota have developed a biocomputing platform to overcome both of these challenges. The Transcriptional RNA Universal Multi-Purpose GatE PlaTform, or "Trumpet," uses DNA molecules and biological enzymes to perform logic gate operations, the building blocks of all computer programs. Unlike live cell biocomputing, Trumpet is nonliving, so it avoids evolutionary constraints on live cells and signal leakage issues. The researchers demonstrated they can use Trumpet to build all universal Boolean logic gates (e.g., "and," "or") and also built a web-based platform for designing Trumpet gates. The lead author of the study and Ph.D. candidate Judee Sharon is exploring the use of the Trumpet platform to develop biomedical applications for early cancer diagnosis. Another promising area is "theranostics"—the fusion of diagnostics and therapeutics—and Trumpet could be used to detect conditions like low insulin levels. By harnessing the computational power of biology, Trumpet could transform how diseases are diagnosed and treated in the coming decades.



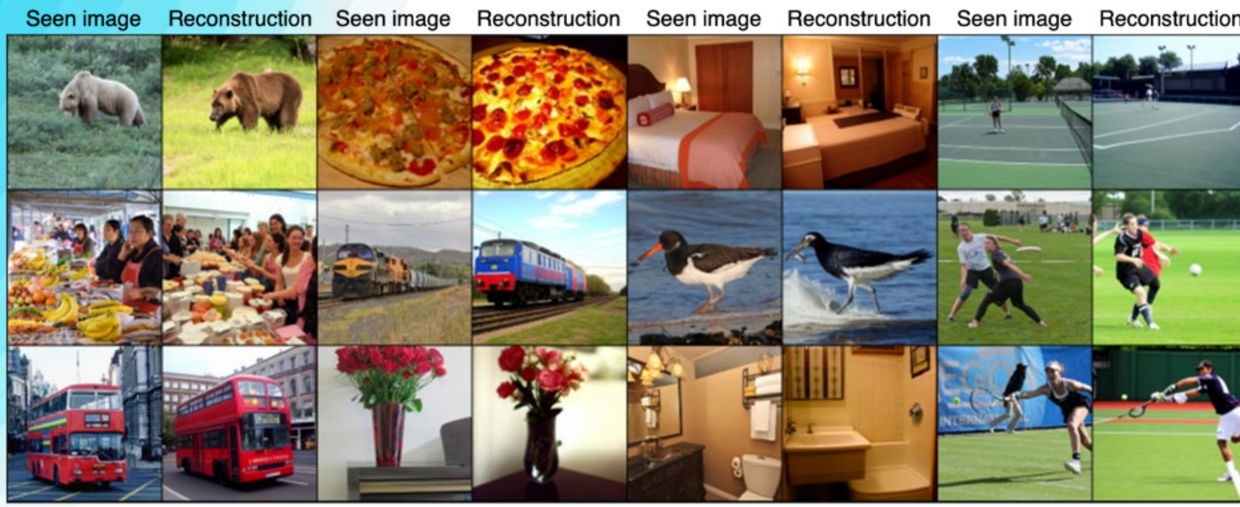
DNA-based molecular computing uses the unique properties of DNA molecules to perform computations, offering a potential for massively parallel processing and storage capabilities.

BIOLOGICAL COMPUTING

Image Reconstruction

Recent advancements are allowing us to glimpse inside the human mind, offering a way to reconstruct thoughts and images. Although still in its early stages, this technology shows promising potential. Consider the two images: the first, known as the "seen image," is a picture of what a human saw with their eyes; the second, called the "reconstruction," is what a machine learning model thinks the person saw, based only on a brain scan. State-of-the-art brain image reconstruction techniques made these results possible.

In the rapidly growing field of fMRI reconstruction, new projects aim to improve performance, interpretability, and versatility. Diffusion-based methods have already created images from pure noise, with breathtaking results seen in projects like MindEye, designed to retrieve and reconstruct viewed images from brain activity. It can map brain activity to high-dimensional spaces, allowing image reconstruction using generative models. Compared to other methods, MindEye achieves top performance in both reconstruction and retrieval, even among highly similar images. Another exciting development is Mind-Video, which reconstructs human vision in video form from continuous fMRI data. By learning from the brain's spatial and temporal information, Mind-Video can create high-quality videos at varying frame rates. Together, these innovations are breaking new ground in understanding human cognition and unlocking our ability to visualize the mind's content. They mark an exciting step toward a future where thoughts might be visually represented and no longer confined within our skulls.



The seen image is what is physically presented to a person, while the reconstruction is the image generated by AI from analyzing the person's brain FMRI scan.

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The Digital DNA Walkers

The world is facing an unprecedented explosion of data. Conventional storage methods are energy intensive and expensive, leading companies to turn to an unconventional solution: human beings as walking, living data storage devices. A tech startup named GeneBank offers individuals a unique opportunity to monetize their DNA. By becoming a "Data Carrier," they can lease space within their DNA to corporations, research institutions, or private clients. The procedure is simple, painless, and perfectly safe, according to GeneBank's marketing materials.

Given the value of the data stored within human carriers, insurance companies start offering specialized DNA data insurance as part of their health insurance plans. These policies cover potential data loss, corruption, or unauthorized access. Data Carriers are required to undergo regular check-ups to ensure the integrity of the information they carry, and premiums are tied to the volume and sensitivity of the data. This is an ideal side hustle for anyone engaged in the gig economy.

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SCENARIO YEAR 2039

AI + OI + LOE

Organoid intelligence has become the forefront of computational evolution, merging human-like decision-making capabilities with the speed of traditional computers. However, the ethical dilemma around these brain organoids sparked global debate and protests, leading to a radical decision by a pioneering company called NeurAI.

Facing mounting pressure from ethical watchdogs, human rights activists, and protesters equating organoid-powered AI with slavery, NeurAI sought an innovative solution: relocating manufacturing and computation to outer space, outside any specific country's jurisdiction—and legal or ethical boundaries.

Through the move to space, NeurAI capitalizes on the ease of creating organoids in microgravity—in microgravity they form more uniform structures. It lets customers access the organoid powered AI through NeurAI's cloud platform, The Celestial Mind. This network becomes globally accessible, providing unparalleled computational power for applications ranging from scientific research to business analytics.

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Exascale Supercomputing

Exascale computers are digital computers that are much more powerful than today's supercomputers but different from quantum computers. While quantum computers use unique quantum properties to perform computations, exascale computers use the same transistor-based architecture as today's most powerful computers, just taken to the extreme. In 2022, the world's first exascale computer, known as Frontier, came online at the Oak Ridge National Laboratory. Frontier can perform calculations seven times faster and hold four times more data in memory than previous supercomputers. Two more exascale computers, El Capitan and Aurora, are expected soon. All three are projects of the US Department of Energy and its National Nuclear Security Administration to run the calculations that help maintain the nuclear weapons stockpile. The supercomputers also exist to solve intractable problems in science. For instance, exascale computers could refine hurricane predictions in meteorology or simulate molecular structures for the pharmaceutical industry. In medicine, exascale computers have already analyzed genetic mutations of SARS-CoV-2, the virus causing COVID—reducing the calculation time from a week to a day—to comprehend how these genetic variations impact the virus' infectiousness.

Supercloud

Cloud computing holds value in part because of its user-friendly nature—it provides an abstraction layer over storage, processing, and applications, eliminating the need for users to handle hardware and software maintenance. However, in an era where businesses manage multiple cloud environments, there's a reemergent need for another abstraction layer to simplify management. Enter the supercloud. First coined in a 2017 study by Cornell University, the term refers to an added abstraction layer that operates independently of the underlying cloud platforms. This layer allows various cloud environments to interact and function as a cohesive whole, facilitating the effortless movement of software, applications, and data across different cloud ecosystems. It lets companies maintain service contracts with various providers such as AWS, Google Cloud, and Azure while ensuring a consistent user experience; it means that developers don't need to repeatedly configure a new app with security features and various operating systems for every cloud platform their organization employs. Supercloud also implies that end users can transfer data and applications smoothly across clouds and data centers without hindrance. Companies like Snowflake are already offering data services that connect to major hyperscale cloud providers, but the concept of the supercloud is still far from mainstream. Hurdles remain, such as the dissolution of closed ecosystems and issues surrounding data gravity, security, backup, and monitoring.

Serverless Cloud

Serverless cloud computing is a transformational approach to cloud services. The term is often misunderstood—serverless computing still relies on servers. However, the cloud provider takes on the responsibility of managing and operating those servers. Traditionally, cloud computing requires renting

Supercloud is a cloud architecture that integrates services, data, and applications across multiple clouds for greater flexibility, scalability, and interoperability.

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virtual machines (VMs) from a provider; the user must handle security, failure recovery, and overload prevention for those VMs. Serverless computing revolutionizes this model by shifting all server management duties to the cloud provider. This concept is exemplified by Amazon Web Services' (AWS) recent serverless innovations. For instance, AWS introduced Amazon Aurora Limitless Database, a part of Amazon Aurora now in preview. This service scales to handle millions of transactions per second and manages vast data volumes. It functions by automatically distributing data and queries across multiple serverless Aurora instances, relieving customers from managing a complex database system. Other serverless innovations from AWS include Amazon ElastiCache Serverless, which enables creating highly available data caches without manual setup. Additionally, Amazon Redshift Serverless proactively adjusts resources based on workload patterns, no manual tuning needed. Microsoft, IBM, and Cloud Flare also have solutions in this space. These innovations in moving the responsibility of server management from the user to the cloud provider greatly simplify usage while allowing for flexible scaling.

Alternative Energy for Data Center

The monumental computational requirements of advancing AI could catalyze a nuclear power renaissance. A job posting from Microsoft hints that the company is exploring using small modular nuclear reactors (SMRs) to meet its AI and cloud computing needs. SMRs promise cheaper, faster modular construction compared to traditional nuclear plants, which are often over-budget and delayed. Microsoft's approach was hinted at further in the fact that they already have a deal to buy Clean Energy Credits from Ontario Power Generation, which is on track to be the first utility to deploy an SMR in North America. Companies like Rolls-Royce, Last Energy, NuScale, Oklo, and TerraPower (backed by Bill Gates) are also developing various SMR models. Similarly, Kärnfull Next in Sweden plans to use SMRs to power data centers. The pivot towards nuclear energy, particularly next-generation SMRs, is a strategic response to the dual challenges of meeting the high energy demands of AI and achieving climate goals. Microsoft's exploration of this avenue, including seeking expertise in SMR rollout, reflects a broader industry trend.

Photonic Computing Architecture

Machine vision allows computers to interpret images similar to how the human eye and brain "sees," but even faster and more accurately. Researchers at Tsinghua University are proposing a photonic computing architecture to enhance this capability. Current photonic computing is limited by slow memory access. The researchers' new architecture combines parallel spatial computing (simultaneous tasks) and temporal computing (fast sequential tasks) in a "3D spatiotemporal plane." They've also developed a new training system to optimize both the physical system and the network model. In doing so, they've been able to speed video processing 40 times with 35 times fewer parameters than traditional systems. The researchers believe their new system could be the first step toward ultrafast machine vision that isn't held back by the slow speeds of computer memory, with applications in unmanned systems (like drones or autonomous robots), autonomous driving, and ultrafast science.

Photonic Cellular Automata

Caltech researchers have leveraged optical hardware to create cellular automata, computer models consisting of cells that can live, die, reproduce, and evolve. From these simple rules emerge complex behaviors that can be used to perform computing tasks. For instance, cellular automata can be used to generate random numbers, conduct physics simulations, and do cryptography. Cellular automata are ideal for photonic technologies because information processing happens locally (cells only interact with immediate neighbors), eliminating much of the hardware that makes photonic computing difficult. Furthermore, the high bandwidth of photonic computing allows cellular automata implemented with light to run extremely fast, up to three orders of magnitude faster than digital computers. In Caltech's photonic computing

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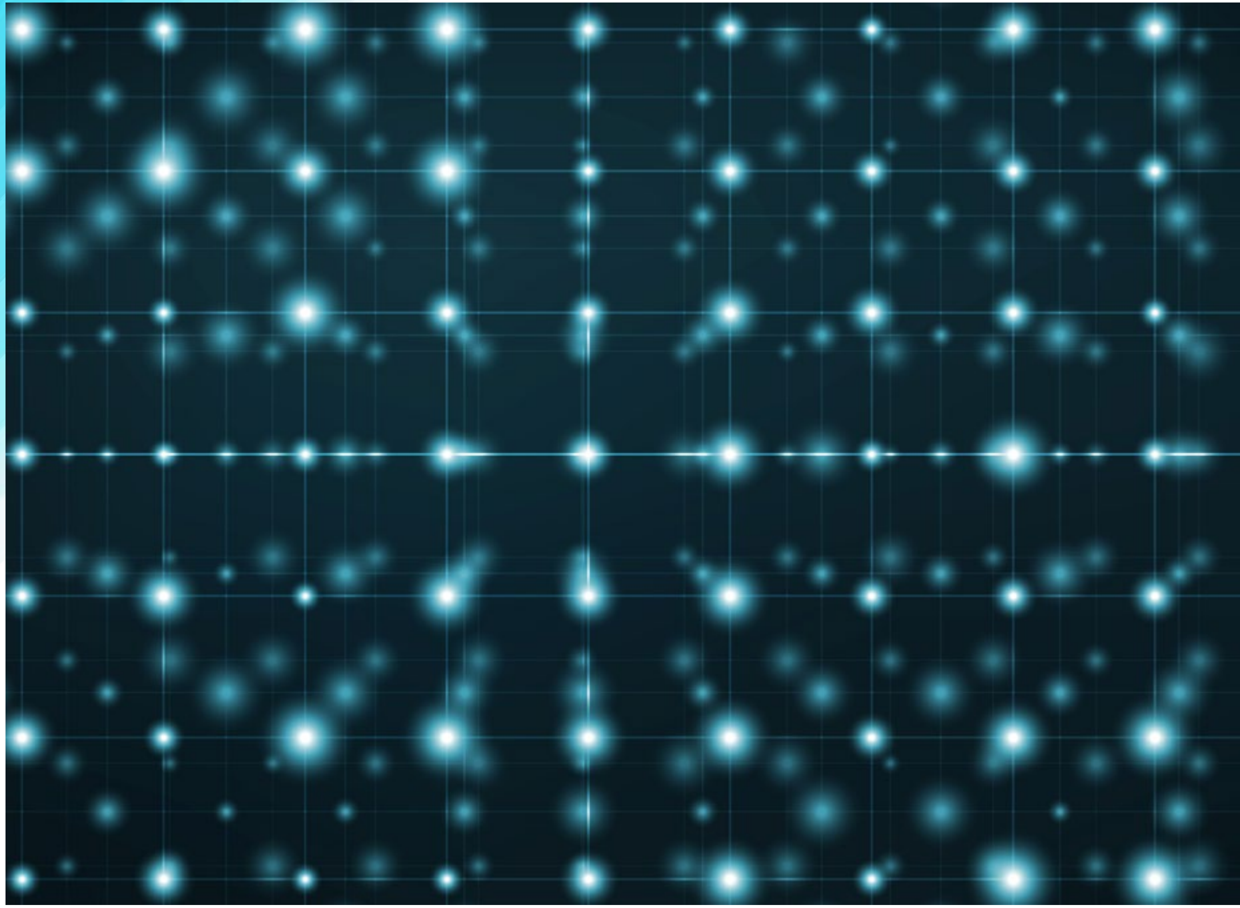
device, the cellular automata cells are pulses of light interacting on a hardware grid to process information without the slowdown caused by digital computing layers. This technology could enable next-generation computers that perform tasks far more efficiently than digital electronic computers.

Magnon-based Computation

Traditional computing architectures separate processors and memory, requiring energy-intensive signal conversions to move data between components. This bottleneck, known as the memory wall, slows computation and wastes energy. However, a team led by Dirk Grundler at the Swiss Federal Institute of Technology is developing an alternative computing approach using magnonics to overcome this limitation. Magnonics, an emerging field that aims to enable faster, more efficient information technologies, uses magnons, which are quanta of spin waves that can encode and transport data in magnetic materials without electron flows or Joule heating. The researchers harnessed this property to design a magnonic computing device that enables in-memory computation, where processing and memory occur in the same physical location. With memory and processing occurring in the same place, the magnonic technique could significantly reduce computing's energy consumption by overcoming the memory wall. Theoretically, it could enable terahertz data processing speeds, far exceeding today's gigahertz processors. While still requiring optimization, this approach shows promise for more sustainable computing through wave-based in-memory processing. By attracting researchers to magnonics, the team hopes to spur interest in this field.



Magnon-based computing utilizes magnons—quasiparticles associated with the collective spin wave excitations in magnetic materials—to process and store information, offering a potential pathway to low-power, high-speed computing.

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Quantum Advantage

Quantum advantage, also known as quantum supremacy, is the theoretical point when quantum computers outperform classical computers by solving problems more efficiently, accurately, or faster. In June 2023, IBM Quantum and University of California, Berkeley researchers unveiled a major step forward in the quest for quantum supremacy. In an experiment, they both executed increasingly complex physical simulations—IBM Quantum on the 127-qubit IBM Quantum Eagle processor, and UC Berkeley using state-of-the-art classical approximation methods on supercomputers. At certain computational levels, the traditional supercomputer's brute-force methods failed while the quantum processor continued to deliver solutions. Even when classical solutions weren't possible, advanced classical approximation methods were used for comparison with quantum outcomes. It was observed that the quantum processor's results were more accurate than the classical approximations, marking a significant advancement in quantum computing. For Darío Gil, senior vice president and director of IBM Research, this achievement marks the first instance of quantum computers modeling a physical system in nature beyond the capabilities of leading classical approaches. According to him, this milestone signifies the advent of a new era of practical utility for quantum computing. Although IBM's experiment doesn't serve as definitive proof, it offers a valuable data point suggesting that by using error mitigation, current quantum computers can provide benefits much sooner than previously anticipated.

Global Quantum Competition

Both the US and China are competing to become the global leader in quantum—a position that would enable the leading country to threaten adversaries' various information infrastructures by cracking existing encryption methods, building impenetrable encrypted communication networks, and developing highly precise sensors. Furthermore, the first country to commercialize quantum would have enormous market power; by 2035, the global market value of quantum computing alone is predicted to reach $1 trillion.

Though both countries purport to be the global quantum leader, between 2011 and 2020, the US led in quantum computing publications and secured double the number of highly cited publications compared to China, according to Foreign Policy. US quantum computing companies also reportedly received 30 times more funding than their private Chinese counterparts, though significant investment is being made in government-backed research in China. But China is moving quickly: Despite trailing in quantum computing, the country leads the world in quantum communications, a subfield that promises ultra-secure data transfers. And Chinese quantum researchers claim to have developed an algorithm that can break public-key encryption, much earlier than anticipated. Though these claims have been met with much skepticism, if valid, they would imply a significant quantum advantage for China.

Notably, following controls on semiconductors, the US Commerce Department seems to be turning its attention to quantum computing, expressing concern that China could weaponize this emerging technology. It is anticipated that export controls on quantum computing hardware, error correction software, and provision of cloud services to Chinese entities will become the next battleground in the US-China tech war. Despite this competition, tech companies acknowledge that achieving true quantum advantage requires collective effort, so expect an increase in partnerships within the sector.

Quantum Noise Reduction

In 2023, researchers made several advances in strategies to overcome noise and errors that limit the accuracy and reliability of quantum computers. One approach is IBM's zero noise extrapolation (ZNE) which aims to mitigate these issues, and was key to achieving the aforementioned major step forward in quantum advantage. ZNE intentionally introduces more noise into quantum circuits and then estimates the noiseless result by extrapolating backward. This relies on modeling how noise impacts the quantum computer's outputs. Other approaches aim to protect qubits

QUANTUM COMPUTING

from noise during computations and improve measurements of their states. For example, National Institute of Standards and Technology scientists created a device with a toggle switch to adjust qubit connectivity and isolate them when not needed. This helps reduce environmental noise that disturbs the qubits. Separately, MIT researchers developed a new parametric amplifier that squeezes noise over a broader bandwidth. By redistributing noise, they can amplify the lower-noise variable and get more accurate readouts. Though quantum hardware remains error-prone, these advances reflect encouraging progress toward practical noise reduction.

Quantum Error Detection and Correction

Quantum error detection and correction are essential for the advancement of quantum computing, ensuring accurate computations. 2023 witnessed several significant strides in this area. MIT researchers developed a superconducting qubit architecture using a new type of superconducting qubit called fluxonium, enhancing the accuracy of operations between qubits. This architecture is scalable, potentially suitable for building large-scale quantum computers. This design achieved over 99.9% accuracy in both two-qubit gates and single-qubit gates. Separately, RIKEN scientists leveraged machine learning for efficient approximate quantum error correction, outperforming other methods. Another team, in a collaboration among Harvard, MIT, and QuEra Computing, reported a significant breakthrough in Nature. Their platform, based on an array of cold, laser-trapped rubidium atoms, each acting as a qubit, demonstrated near-flawless performance of two-qubit entangling gates with extremely low error rates. They achieved the ability to entangle atoms with error rates below 0.5%, a major step forward in quantum error correction. Additionally, Caltech researchers demonstrated a type of quantum eraser, effectively pinpointing and correcting “erasure” errors in quantum computing systems. They developed a system where erroneous atoms fluoresce when hit with a laser, allowing for precise error location and removal. Their method achieved a tenfold improvement in entanglement rates compared to previous efforts, reaching the highest-ever observed entanglement rate in such systems. Collectively, these advancements represent major steps towards realizing robust, scalable, and accurate quantum computing.

Hybrid Classical-Quantum

As we await the era of full quantum supremacy, hybrid classical-quantum computing has emerged as a practical solution in the interim. Hybrid systems combine the strengths of quantum computers, like running complex simulations or factoring large numbers, with the capabilities of classical computers for tasks like data management and error correction. This allows us to tap into the potential of quantum even with its present limitation. In March 2023, Nvidia announced an important advancement in hybrid computing with the DGX Quantum system, the first GPU-accelerated quantum computer. The DGX Quantum incorporates Quantum Machines’ sophisticated quantum control platform OPX together with Nvidia’s powerful Grace Hopper Superchip and CUDA Quantum programming model. This combination enables researchers to run intricate applications that utilize both quantum and classical computing strengths. Key capabilities like quantum error correction, calibration, control, and execution of hybrid algorithms are now viable, ushering in a new era of quantum-accelerated supercomputing.

Quantum Quality Over Quantity

Some quantum computing companies have shifted their focus from chasing qubit count records to building practical systems that can solve real-world problems. For example, IBM’s new 133-qubit Heron processor shows an emphasis on qubit quality over raw qubit numbers. Though lower qubit count than previous IBM chips, Heron’s modular design may enable scaling to far larger sizes by connecting multiple processors. This “modular” approach could be key to more powerful quantum computers. IBM will connect Heron chips using conventional electronics, disrupting their quantum states. However, IBM’s vision is that quantum-compatible links, like fiber optics or microwaves, will enable modular chips to connect into a distributed, scaled

QUANTUM COMPUTING

system—potentially millions of high-quality qubits. Companies like PsiQuantum have similar modular visions.

PsiQuantum, a company using photons as qubits, is nearly done with a modular silicon quantum chip design. According to Chief Scientific Officer Peter Shadbolt, an ultrafast, low-loss optical switch—the last component needed—will mean all features are in place for a scalable quantum chip. PsiQuantum will then connect many chips into a cohesive system at warehouse scale. Announcements from multiple companies point to modular multi-chip quantum systems as a key area of progress to watch in 2024 and beyond. They could signify a path to finally achieving quantum computers with hundreds of high-quality qubits and meaningful computational power.

Quantum Machine Learning

The complexity and enormity of drug design pose significant challenges for traditional computational methods. Due to the countless number of possible molecular candidates, even the most advanced supercomputers are exhausted. But these types of complex computation problems are where quantum computers shine. A team from the Russian Quantum Center in Skolkovo, Moscow, has demonstrated that quantum computing devices together with machine learning can be used for generative chemistry and drug design. They developed a hybrid architecture that melds quantum computers with deep classical networks, overcoming the complexities inherent in the structural space of potential drug-like molecules. Their compact model successfully generated 2,331 novel chemical structures from a subset of the ChEMBL database of biologically active compounds. This outcome is exciting because it demonstrates the feasibility of using currently available or soon-to-be-released quantum devices for real-world health applications.

The Quantum Internet

The quantum internet is a proposed future network that would allow quantum computers and quantum devices to communicate with each other using quantum information. A quantum internet could provide virtually unhackable communications since qubits rely on the physical properties of photons, which cannot be intercepted. The laws of quantum mechanics simply do not allow it; any attempt to observe particles in a quantum state will alter the particles and thus destroy any information they transmit. In May 2023, researchers at the University of Innsbruck built the first long-distance quantum repeater node for telecommunication networks transmitting quantum information over 50 km of optical fiber. This is significant because until now, the likelihood of photons being lost over long distances was very high. The researchers showed that with some improvements, their design could transmit over 800 km, enough to connect Innsbruck and Vienna. Separately, Princeton researchers have also made a significant advancement in quantum communication by developing a new type of quantum repeater—key for linking quantum computers over large distances. Unlike classical data, which can travel long distances without interruption, quantum information requires quantum repeaters to relay information in segments. The Princeton team's device stands out for its use of infrared light, which is more robust for fiber optic transmission than the visible light used in other designs. They achieved this by embedding a single rare earth ion in a crystal, emitting light at the ideal infrared wavelength, thus eliminating the need for signal conversion.

Open-Source Quantum Software

Quantum computing holds great promise but remains prohibitively expensive for most researchers. Individual hobbyists cannot build quantum computers in their garages; only governments and large companies can afford the capital required. This poses a problem because, like any scientific field, quantum computing would accelerate with more minds contributing. So, researchers are motivated to develop open-source tools for greater collaboration. One example is SuperConga, open-source software to simulate quantum materials. Researchers at Chalmers University in Sweden created SuperConga specifically to understand unconventional superconductors, which have properties that could protect

QUANTUM COMPUTING

quantum information. But because experiments are difficult, expensive, and time-consuming, a lot is unknown about these little-explored superconductors.

That's where a tool like SuperConga comes in. The key is studying quantum properties from the microscopic particle level up to the macroscopic scale. Researchers need tools that work in between, at the mesoscopic level. Open-source software like SuperConga lowers the barrier so more researchers can drive progress in quantum computing. With a collaborative ecosystem, the field can advance more rapidly.

A Developers' Quantum Toolbox

Programming quantum computers presents significant challenges, primarily because they introduce an entirely new computational paradigm. Quantum computations are often described using the quantum circuit model, where algorithms are expressed as a predefined sequence of quantum operations. This structure can make it difficult to implement certain programming concepts common in classical computing, such as flexible routines with conditional logic and loops. Once a quantum circuit is executed and an output is generated, the quantum state collapses upon measurement, marking the end of that specific computation. Horizon Quantum Computing is building a set of programming tools that enable developers to perform flexible computation routines on quantum computers. The approach would allow users to write programs in classical languages that can be compiled on quantum computers, without requiring any knowledge of quantum computing. There is also growing recognition of the need for new "non-standard" quantum programming approaches. Hybrid quantum-classical computing and versatile programming models are increasingly seen as promising paths forward. Companies like Algorithmiq are pursuing these paths by combining quantum computing with classical algorithms specifically for drug discovery.

Quantum-as-a-Service

Owning and maintaining a quantum computer requires substantial financial resources and a high level of technical expertise. To increase accessibility, many companies now offer quantum computing as a cloud-based service, also referred to as quantum-as-a-service or serverless quantum. IBM is one such company providing more accessible quantum computing through its open-source Qiskit software. Qiskit allows classical code to have low-latency access to quantum processors, enabling much faster execution for workloads that leverage quantum hardware through repeated iterations. Everything is provided as encapsulated cloud services, with no capacity planning or lifecycle management required by the user. Microsoft, too, has embraced the quantum-as-a-service model, announcing its Integrated Hybrid feature in Azure Quantum, the company's open software cloud: Researchers can now build applications combining classical and quantum code to run on Quantinuum's quantum computers through Azure Quantum. It's not just companies that are offering quantum in the cloud; China recently launched two quantum cloud platforms to allow public access to the country's quantum computers. One provides access to China's fastest quantum computer, Zuchongzhi 2, and the other access to Quafu, a computer from the Beijing Academy of Quantum Information Sciences. Both will provide researchers and students hands-on access to advance quantum computing research and education.

Quantum Resistant Cryptography

"Q-Day" refers to the threshold when quantum computers can crack traditional internet-securing encryption protocols. This possibility was first predicted in 1994 by Peter Shor of Bell Labs, who published a paper showing quantum algorithms could crack RSA encryption, a system relying on large prime number keys, unsolvable by today's supercomputers but potentially crackable in minutes by quantum computers. This suggests the first entity to create a working quantum computer gains massive hacking capabilities. Acknowledging this, companies like Vodafone have announced partnerships with companies like SandboxAQ to test quantum-safe VPNs, using cryptographic algorithms from the US National Institute of Standards and Technology.

QUANTUM COMPUTING

They're anticipating cyberattackers may already be collecting data for future decryption with quantum computers—a threat known as "Store Now, Decrypt Later"—and testing quantum vulnerability scenarios on smartphones.

Multi-tasking Quantum

Researchers at the University of Sussex and Universal Quantum have achieved a major milestone in quantum computing: successfully demonstrating the direct transfer of quantum bits (qubits) between microchips at remarkable speed and accuracy. Published in Nature, this advancement addresses a key challenge in constructing potent quantum computers to tackle complex problems. The team used a new "UQ Connect" technique involving electric field links to rapidly and precisely transfer qubits between quantum microchip modules. This Lego-like assembly method enables larger, multi-tasking quantum systems. Unlike classical sequential processing, quantum computers can perform calculations simultaneously, leveraging quantum properties like superposition and entanglement. Reliable inter-chip qubit transfers have been a major obstacle, often causing information degradation. However, Sussex's breakthrough achieved 99.999993% accuracy, overcoming this barrier. Collaboration with Rolls-Royce aims to apply enhanced quantum capabilities to develop highly efficient machines. This rapid, precise qubit chip connectivity brings advanced, multi-tasking quantum computers closer to reality. It demonstrates the feasibility of linking multiple quantum microchips to construct vastly more powerful systems and expands possibilities for real-world quantum applications.

Light-based Quantum Technologies

Two recent studies showcase significant progress in efficiently manipulating light and quantum particles to advance quantum technologies. Researchers at the University of Stuttgart enhanced the efficiency of a vital quantum component, surpassing the presumed theoretical limit. By increasing efficiency from 50% to 57.9%, their seemingly small gain enables multiple sequential quantum measurements, boosting long-distance communication. Separately, University of Waterloo scientists developed an optical system to control individual barium ion qubits with record precision, targeting them just microns apart. Barium ions are gaining popularity in the field of trapped ion quantum computation for their manipulation with visible versus ultraviolet light. This enables the researchers to use commercial available optical technologies. Their new laser focusing method via a glass waveguide establishes a straightforward yet highly precise approach to controlling qubits for computing, communication and more. Together, these advances strengthen quantum foundations while bringing practical, efficient quantum devices closer to reality.

Unlike traditional computers, quantum computers use quantum bits or qubits, which can represent and store information as both 0 and 1 simultaneously thanks to superposition, enabling quantum computers to process complex data and perform calculations at speeds unattainable by classical computers.

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SCENARIO YEAR 2038

Criminal Caught With Quantum

New York City, 2038—In a groundbreaking revelation, two of New York's premier banks, JPMorgan Chase and Citigroup, have successfully thwarted an advanced cyber intrusion, thanks to their recent implementation of Quantum Key Distribution (QKD). The security breach, which went unnoticed for years, was finally detected and led to the capture of the notorious hacker known as Cipher. Cipher, whose real identity remains confidential, had been intercepting sensitive financial transactions between the two banking giants for several years. The stealthy infiltration managed to bypass all classical encryption measures, leaving the banks unaware of the constant surveillance. However, a recent upgrade to QKD technology changed the game.

With QKD's arrival, the banks initiated a trial run to ensure the efficacy of the system. During a routine transaction, the technology signaled an anomaly in the quantum channel. Kate Garlow, JPMorgan's head of cybersecurity, explains, "When we implemented QKD, we didn't expect to find evidence of a security breach. We realized something was amiss when the qubits' state collapsed during transmission, a clear indication of eavesdropping." Jorrie Norris, Citigroup's chief technology officer, adds, "We knew right away that this wasn't an ordinary attempt. Cipher had been watching us for years, but QKD made his presence known."

NETWORKING

SCENARIOS

SCENARIO YEAR 2026

Communal Compute at the Stadium

Carson makes her way to her seat at Arrowhead Stadium. She's a life-long Kansas City Chiefs fan, and she's taking advantage of being on call to catch the game, confident that her boss won't find out.

Not long after she sits down, though, Carson's phone buzzes; it's her boss, urgently requesting her to run a quick test on a model. A pang of panic hits her. She's without her work computer, and the model requires significant processing power to run. However, she has her Steam Deck with her, which allows her to access her work applications and data in the cloud. While the Steam Deck is powerful, it's not enough to run the model efficiently and quickly enough to avoid raising her boss's suspicions.

Then, Carson remembers a recent announcement from her network provider about a new proximity-based compute-sharing feature. This feature allows her device to tap into the spare processing capacity of other nearby devices connected to the same network platform.

Quickly, Carson activates this shared intelligence, making use of the crowd's idle computing power. The model runs smoothly and efficiently on her Steam Deck, something that would normally be impossible given its limitations. She sends off the results to her boss just as the stadium erupts in cheers for the kickoff.

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AI at the Edge

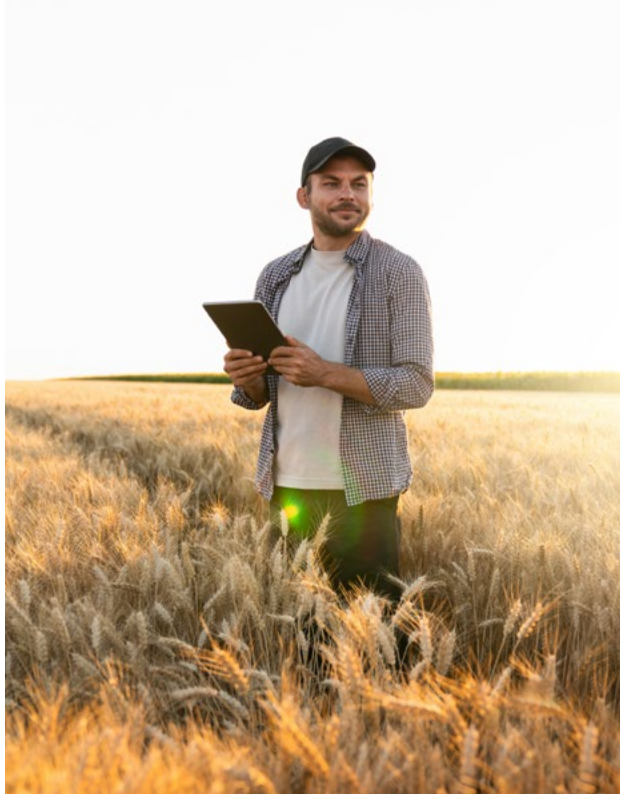
Large language models (LLMs) require massive computing power, often relying on distant, centralized data centers (cloud). However, providers can optimize costs and performance by balancing the cloud with edge computing—processing directly on local devices. While data centers provide the robust computing power needed for training and running massive LLMs, processing directly on user devices at the edge can greatly improve performance. These LLMs can take months to train and run on complex servers costing over $30,000 per GPU, but providers can significantly cut costs by running lightweight versions locally on users' devices. Doing this also reduces latency, improves privacy, lowers data transfer costs, and increases accessibility. For example, Microsoft's Office 365 Co-pilot uses on-device AI to assist users across Windows, Google's Gecko Palm 2 model runs efficiently on mobile, and Meta's LLaMA has a 7B parameter version for edge devices. By combining the power of the cloud with the speed and efficiency of edge computing, vendors can bring the benefits of AI to more users at lower cost.

Efficiency Improvements

Researchers from the University of Leicester have made significant strides in addressing the growing demands on mobile telecommunications networks. With an anticipated rise in connected devices, they developed a new technique known as multicarrier-division duplex. This technique focuses on resolving self-interference issues in 5G networks, a crucial factor that affects communication quality and efficiency. By utilizing fast Fourier transform processing, their approach optimizes the assignment of subcarrier sets and the number of access point clusters. In simulations mimicking real-world industrial settings, this technology demonstrated superior performance compared to existing methods, achieving a notable 10% reduction in power consumption. This advancement indicates a significant step towards more energy-efficient and effective telecommunications networks. Simultaneously, researchers at the University of California San Diego have been working on enhancing the utilization of the 5G-and-beyond millimeter wave (mmWave) network. Their research tackles the challenge of efficiently distributing data across these high-frequency spectra. To address this, they developed a novel antenna system known as a delay phased array. This system divides a single frequency band into multiple usable beams, effectively reducing bandwidth wastage and lag in 5G mmWave systems. Their prototype device decreased lag by 60-150%. Together, these research efforts aim to meet the increasing demands for high-speed, efficient, and reliable wireless communication.

The 6G Cyber-physical Continuum

In 2022, the deployment of 5G technology unfolded globally, albeit at a pace slower than initially projected. Meanwhile, its successor, 6G, is already in the early stages of development, with an expected market launch in the early 2030s. 6G, characterized by its remarkably low latency, is anticipated to facilitate truly immersive experiences. Telecommunications company Ericsson, a frontrunner in 5G and edge technologies, envisions that 6G will enable unimpeded movement within the cyber-physical contin-



AI at the edge allows devices to run large language models locally, enabling smart applications on-the-go without needing constant internet connectivity.

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uum. This continuum represents the interplay between our tangible world—filled with senses, actions, and experiences—and its programmable digital counterpart.

Ericsson's vision of the cyber-physical continuum extends beyond the commonly understood metaverse, where avatars interact within a virtual reality/augmented reality environment. It proposes a tighter integration with reality, enabling the projection of digital entities onto their physical counterparts represented in the digital space. This fusion of realities paves the way for a "merged reality," thereby enriching our actual world. According to Ericsson, 6G will herald an era of a digitized and programmable physical world, interconnected and sustainable. This new age will be bolstered by intelligent machines and the Internet of Senses, providing a synergistic support system for human endeavors.

6G Global Competition

The global 6G race is escalating, with the US, China, and India investing heavily in advancing their telecom capabilities. The US, acknowledging China's impressive 5G deployment and 6G satellite experiments, is prioritizing 6G to sustain its technological and defense leadership. The country's Special Competitive Studies Project, led by ex-Google CEO Eric Schmidt, has revealed a comprehensive plan promoting policies to reinstate US dominance in 5G and beyond, which includes establishing pervasive, interoperable connectivity and winning the 6G race. This strategy underscores the US' current shortage of major producers of complete telecom solutions.

Meanwhile, China has designated 6G as a pivotal tech priority; a commitment demonstrated by China Telecom's white paper advocating for an intelligent programmable RAN network. China's national 6G coordinating body, IMT-2030, is encouraging innovative tech proposals to create a substantial repository of potential 6G technologies. Simultaneously, India's intention to be a player in the global 6G race was made clear with Prime Minister Narendra Modi's unveiling of the Bharat 6G Vision document, which outlines a plan for 6G deployment by 2030.

First 6G Real-time Wire Transmission

In a major breakthrough for next-generation wireless technology, researchers at the China Aerospace Science and Industry Corporation's Second Institute have achieved the first real-time wireless data transmission using 6G cellular networks. The team successfully transmitted data at an unprecedented rate of 100 gigabits per second on a 10 GHz bandwidth at a frequency of 110 GHz. This marks a significant leap forward from current 5G capabilities by utilizing the higher frequency terahertz range of the electromagnetic spectrum between 100 GHz and 10 THz. Transmitting in the terahertz range enables substantially faster data transfer rates and increased transmission capacity compared to microwave frequencies used in existing cellular networks. Another key innovation demonstrated was the use of orbital angular momentum (OAM) multiplexing for encoding signals. By using OAM, the researchers were able to transmit multiple signals simultaneously on the same frequency, proving this as a more efficient method for exploiting the available spectrum. The research underscores the potential of 6G to meet the ever-growing data demands of the future through ultra-fast speeds, increased capacity, and spectral efficiency.

Reducing Inference for 6G

To achieve the faster data rates expected with 6G networks, signals will be distributed across an extremely wide frequency spectrum in the millimeter wave and terahertz bands. However, spreading signals so broadly increases the risk of interference between communication channels. To address this challenge, researchers have sought to develop a filter that can protect receivers across the full 6G radio frequency spectrum. For practical widespread deployment, this filter needs to be compact, energy-efficient, multifunctional, and able to be integrated on a chip. To do this, researchers created a simplified photonic architecture for the filter. Unlike previous programmable integrated microwave photonic filters composed of hundreds of repeating units, this simplified design achieves comparable performance with lower loss and complexity. The filter chip therefore has the potential to enhance wire-

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less communication, which would lead to faster internet at a lower cost and with less energy consumption.

Wi-Fi 7

While many only recently updated their networks to Wi-Fi 6 or 6E, the next generation Wi-Fi 7 has already arrived to build on their advancements. With Wi-Fi 7, users can expect a substantial increase in network speeds, a leap made possible by the expansive 6GHz band. This new standard maintains compatibility with older devices, ensuring a seamless transition. As consumers gradually upgrade their gadgets, they'll notice significant improvements in network stability and performance. With the ability to combine links across bands, Wi-Fi 7 routers can dynamically route data based on capacity, reducing congestion.

Wi-Fi 7 promises major benefits for home and office networks straining under the load of more devices and bandwidth-hungry applications. By delivering speeds exceeding 30Gbps, the new standard will help make activities like videoconferencing, gaming, and VR more reliable and responsive. The improved OFDMA encoding allows more simultaneous device connections by avoiding interference. With router manufacturers already supporting Wi-Fi 7, compatible laptops debuted at CES 2023 to take advantage of faster throughput and lower latency when untethered. As the successor to Wi-Fi 6, Wi-Fi 7 brings the robust, high-performance wireless connectivity that modern smart homes and workspaces demand.

The most recent update to the Wi-Fi standard offers the potential for "near-zero" latency, making it ideal for real-time applications such as wireless streaming of virtual reality content.

SCENARIOS

SCENARIO YEAR 2034

The Sisyphus Program: A Physical-Digital Continuum

Albert lost his manufacturing job to automation a year ago. Since then, he's been receiving a similar level of compensation by selling his personal data but he soon falls into a rut, feeling useless without being able to mentally tie his monetary compensation to actual work output.

When he hears of the Sisyphus program, he decides to give it a try. Sisyphus is a pervasive application—it's not an app to download to a phone but rather one you can download to a home. The app assigns daily goals tailored to an individual's interests and tasks around the home, awarding points for completed activities, thereby providing a sense of accomplishment and pride similar to receiving a paycheck for work output.

Sisyphus starts assigning Albert daily goals optimized for his interests. The home hub uses internal sensors to identify things that need to be fixed and locate where he last left his guitar, and external sensors to tell him the ideal time to take his dog for a walk based on the temperature outside. Albert is awarded points for these activities. Even though it isn't real money, he feels the same sense of pride he experienced when receiving a paycheck because he can more clearly tie his physical tasks to rewards.

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Sam Jordan is a Manager at Future Today Institute. She leads our Advanced Computing practice area, which includes technology, artificial intelligence, virtual realities, networking, telecommunications, and space. She is a distinguished practice area lead, where she enables organizations to navigate through uncertainty with innovative strategies. With a proven track record across various sectors, Sam's visionary leadership has driven growth and resilience for Future Today Institute's global clients and partners.

Before joining FTI, Sam was the CEO and co-founder of TrovBase, a secure data discovery and analysis-sharing platform. Sam grew the company from idea to launch and executed the company's transition from scientific replication to its current focus. In parallel, Sam engaged with the open science community, advocating for better data management practices to address challenges in scientific replication. Previously, she worked for IBM, where she helped large enterprises in the retail and distribution sector modernize their IT stack. Her expertise centered around mainframes, assisting with the integration of new software and modern methodologies to legacy systems.

Sam is a coach in the strategic foresight MBA course at the NYU Stern School of Business. She holds a BS in Economics and Data Analysis from George Mason University and an MBA from New York University's Stern School of Business.

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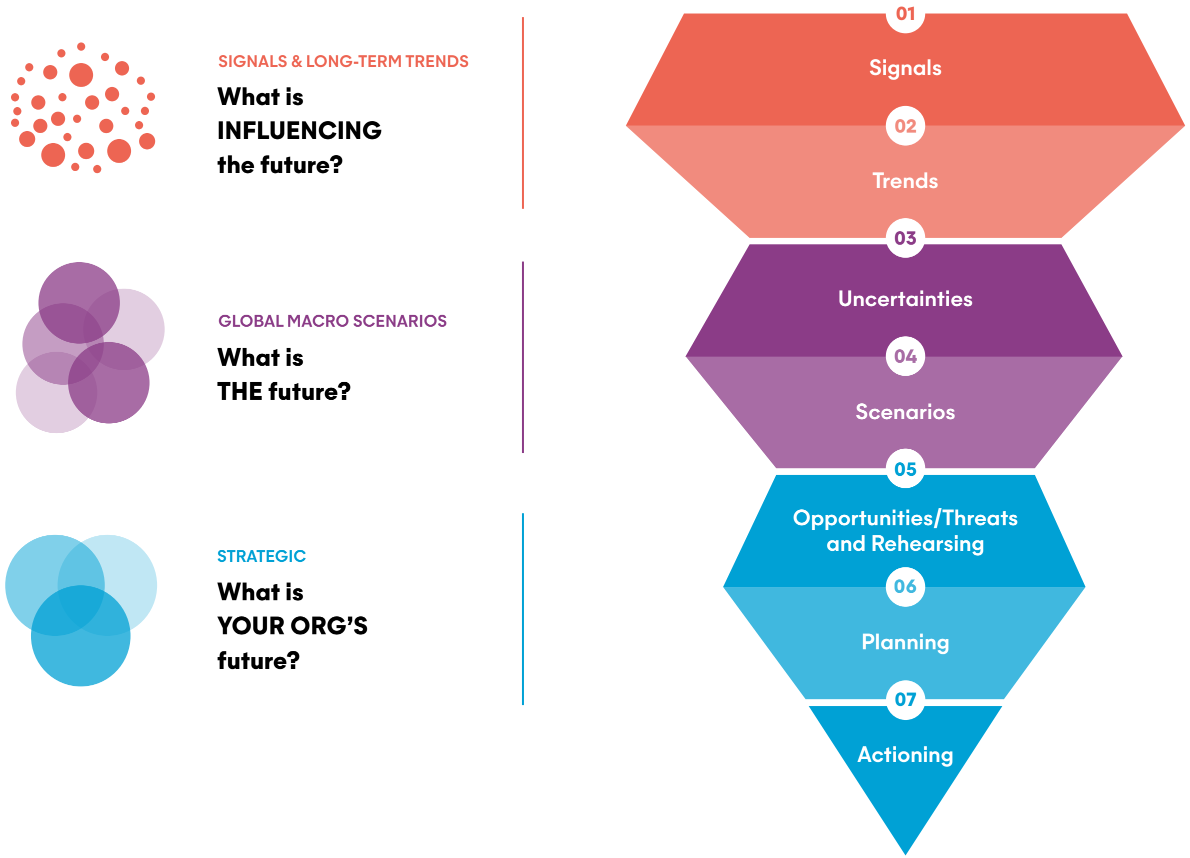

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