STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2025

A Preview of the 2025 Report on Ten Key Technologies and Their Policy Implications

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FOREWORD

In every era, technological discoveries bring both promise and risk. Rarely, however, has the world experienced technological change at the speed and scale we see today. From nanomaterials that are fifty thousand times smaller than the width of a human hair to commercial satellites and other private-sector technologies deployed in outer space, breakthroughs are rapidly reshaping markets, societies, and geopolitics. What's more, US technology policy isn't the unique province of government like it used to be. Instead, inventors and investors are making decisions with enormous policy consequences, even if they may not always realize it. Artificial intelligence (AI) algorithms are imbued with policy choices about which outcomes are desired and which are not. Nearly every new technology, from bioengineering new medicines to building underwater research drones, has both commercial and military applications. Private-sector investment, too, simultaneously generates both national advantages and vulnerabilities by developing new capabilities, supply chains, and dependencies, and by pursuing commercial opportunities that may not serve long-term national interests.

While engineers and executives need to better understand the policy world, government leaders need to better understand the engineering and business worlds. Otherwise, public policies intended to protect against societal harms may end up accelerating them, and efforts to align innovation with the national interest could end up harming that interest by dampening America's innovation leadership and the geopolitical advantages that come with it.

In these complex times, the only certainties are that uncertainty is rampant and the stakes are high: Decisions made today in boardrooms, labs, and government offices are likely to set trajectories for the United States and the world for years to come.

Now more than ever, understanding the landscape of discovery and how to harness technology to forge a better future requires working across sectors, fields, and generations. Universities like Stanford have a vital role to play in this effort. In 2023, we launched the Stanford Emerging Technology Review (SETR), the first-ever collaboration between Stanford University's School of Engineering and the Hoover Institution. Our goal is ambitious: transforming technology education for decision makers in both the public and private sectors so that the United States can seize opportunities, mitigate risks, and ensure that the American innovation ecosystem continues to thrive.

This is our latest report surveying the state of ten key emerging technologies and their implications. It harnesses the expertise of leading faculty in science and engineering fields, economics, international relations, and history to identify key technological developments, assess potential implications, and highlight what policymakers should know.

This report is our flagship product, but it is just one element of our continuous technology education campaign for policymakers that now involves nearly one hundred Stanford scholars across forty departments and research institutes. In the past year, SETR experts have briefed senior leaders across the US government—in Congress and in the White House, Commerce Department, Defense Department, and US intelligence community. We have organized and participated in fifteen Stanford programs, including multiday AI and biotechnology boot camps for congressional staff; SETR roundtables for national media and officials from European partners and allies; and workshops convening leaders across sectors in semiconductors, space technology, and bioengineering. And we are just getting started.

Our efforts are guided by three observations:

1. America's global innovation leadership matters.
American innovation leadership is not just important for the nation's economy and security. It is the linchpin for maintaining a dynamic global technology innovation ecosystem and securing its benefits.

International scientific collaboration has long been pivotal to fostering global peace, progress, and prosperity, even in times of intense geopolitical competition. During the Cold War, American and Soviet nuclear scientists and policymakers worked together to reduce the risk of accidental nuclear war through arms control agreements and safety measures. Today, China's rise poses many new challenges. Yet maintaining a robust global ecosystem of scientific cooperation remains essential—and it does not happen by magic. It takes work, leadership, and a fundamental commitment to freedom to sustain the openness essential for scientific discovery. Freedom is the fertile soil of innovation, and it takes many forms: the freedom to criticize a government; to admit failure in a research program as a step toward future progress; to share findings openly with others; to collaborate across geographical and technical borders with reciprocal access to talent, knowledge, and resources; and to work without fear of repression or persecution. In short, it matters whether the innovation ecosystem is led by democracies or autocracies. The United States has its flaws and challenges, but this country remains the best guarantor of scientific freedom in the world.

2. Academia's role in American innovation is essential—and at risk.
The US innovation ecosystem rests on three pillars: the government, the private sector, and the academy. Success requires robust research and development (R&D) in all three. But they are not the same, and evidence increasingly suggests that universities' role as the engines of innovation is at a growing risk.

Universities, along with the US National Laboratories, are the only institutions that conduct research on the frontiers of knowledge without regard for potential profit or foreseeable commercial application. This kind of research is called basic or fundamental research. It takes years, sometimes decades, to bear fruit. But without it, future commercial innovations would not be possible. Radar, global positioning systems (GPS), and the internet all stemmed from basic research done in universities. So did the recent "overnight success" of the COVID-19 mRNA vaccines, which relied on decades of university research that discovered mRNA could activate and block protein cells and figured out how to deliver mRNA to human cells to provoke an immune response. Similarly, the cryptographic algorithms protecting data on the internet today would not have been possible without decades of academic research in pure math. And many of the advances in AI, from ChatGPT to image recognition, build on pioneering work done in university computer science departments that also trained legions of students who have gone on to found, fund, and lead many of today's most important tech companies. In many ways and in nearly every field, America's innovation supply chain starts with research universities.

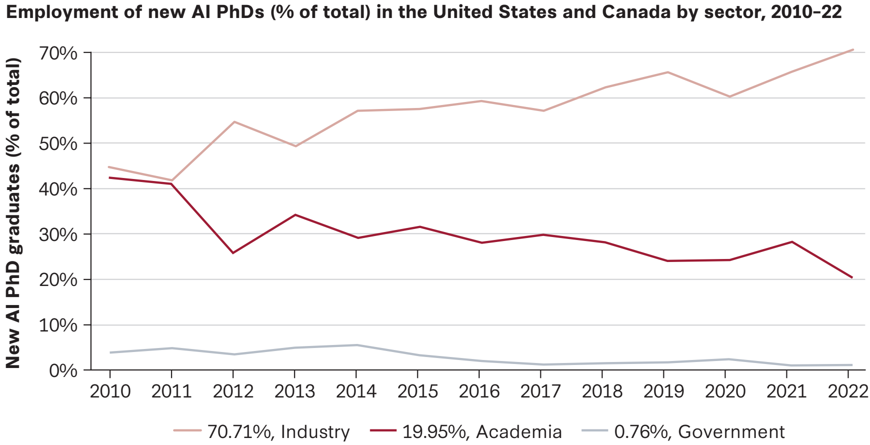
Yet evidence suggests that the engine of innovation in US research universities is not running as well as it could, posing long-term risks to the nation. In 2024, for the first time, the number of Chinese contributions surpassed ones from the United States in the closely watched *Nature* Index, which tracks eighty-two of the world's premier science journals. Funding trends are also heading in the wrong direction. The US government is the only funder capable of making large and risky investments in the basic science conducted at universities (as well as at national laboratories) that is essential for future applications. Yet federal R&D funding has plummeted in percentage terms since the 1960s, from 1.86 percent of GDP in 1964 to just 0.66 percent of GDP in 2016. The Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act of 2022 was supposed to turn the tide by dramatically raising funding for basic research, but major increases were subsequently scrapped in budget negotiations. The United States still funds more basic research than China does, but Chinese investment is rising six times faster—and is expected to overtake US spending within a decade.

Although private-sector investment in technology companies and associated university research has increased substantially, it is not a substitute for federal funding, which supports university R&D directed at national and public issues, not commercial viability.

To be sure, the rising dominance of private industry in innovation brings significant benefits. But it is also generating serious and more hidden risks to the health of the entire American innovation ecosystem. Technology and talent are migrating from academia to the private sector, accelerating the development of commercial products while eroding the foundation for the future. We are already reaching a tipping point in AI. In 2022, more than 70 percent of students who received PhDs in artificial intelligence at US universities took industry jobs, leaving fewer faculty to teach the next generation. As the bipartisan National Security Commission on Artificial Intelligence put it, "Talent follows talent."

Today, only a handful of the world's largest companies have both the talent and the enormous computing power necessary for developing sophisticated large language models (LLMs) like ChatGPT. No university comes close. In 2024, for example, Princeton University announced that it would use endowment funds to purchase 300 advanced Nvidia chips to use for research, costing about $9 million, while Meta announced plans to purchase 350,000 of the same chips by year's end, at an estimated cost of $10 billion.

FIGURE 1 Most new AI PhDs hired in North America are flocking to industry



SOURCE: Adapted from Nestor Maslej, Loredana Fattorini, Raymond Perrault, et al., *The AI Index 2024 Annual Report*, AI Index Steering Committee, Institute for Human-Centered AI, Stanford University, Stanford, CA, April 2024. Data from CRA Taulbee Survey, 2023

These trends raise several concerning implications. A very significant one is that research in the field is likely to be skewed to applications driven by commercial rather than public interests. The ability for universities—or anyone outside of the leading AI companies—to conduct independent analysis of the weaknesses, risks, and vulnerabilities of AI (especially LLMs recently in the news) will become more important and simultaneously more difficult. Further, the more that industry offers unparalleled talent concentrations, computing power, training data, and the most sophisticated models, the more likely it is that future generations of the best AI minds will continue to flock there (see figure 1)—potentially eroding the nation's ability to conduct broad-ranging foundational research in the field.

3. The view from Stanford is unique, important—and needed now more than ever.

Stanford University has a unique vantage point when it comes to technological innovation. It is not an accident that Silicon Valley surrounds Stanford; technology developed at Stanford in the 1930s served as the foundation for the pioneering companies like Varian Associates and Hewlett-Packard that first shaped industry in the region. Since then, the university has continued to fuel that innovation ecosystem. Stanford faculty, researchers, and former students have founded Alphabet, Cisco Systems, Instagram, LinkedIn, Nvidia, Sun Microsystems, Yahoo!, and many other companies, together generating more annual revenues than most of the world's economies. Start-ups take flight in our dorm rooms, classrooms, laboratories, and kitchens. Technological innovation is lived every day and up close on our campus—with all its benefits and downsides. This ecosystem and its culture, ideas, and perspectives often seem a world apart from the needs and norms of Washington, DC. Bridging the divide between the locus of American policy and the heart of American technological innovation has never been more important.

Stanford has a rich history of policy engagement, with individuals who serve at the highest levels of government as well as institutional initiatives that bring together policymakers and researchers to tackle the world's toughest policy problems. And as Stanford's School of Engineering celebrates its one hundredth anniversary in 2025, we are reminded of the profound impact that generations of Stanford faculty, students, and staff have had through their discoveries—from the klystron, a microwave amplifier developed in the 1930s that enabled radar and early satellite communications; to the algorithms driving Google; to optogenetics, a technique pioneered in 2005 that uses light to control neurons, enabling precise studies of brain function. In this moment of rapid technological change, we must do even more to connect emerging technologies with policy. We are proud and excited to highlight this collaboration between Stanford's Hoover Institution and the School of Engineering to bring policy analysis, social science, science, medicine, and engineering together in new ways.

Today, technology policy and education efforts are often led by policy experts with limited technological expertise. The Stanford Emerging Technology Review flips the script, enlisting ten of the brightest scientific and engineering minds at the university to share their knowledge of their respective fields by working alongside social scientists to translate their work for nonexpert audiences. We start with science and technology, not policy. And we go from there to emphasize the important interaction between science and all aspects of policy.

How to Use This Report: One Primer, Ten Major Technology Areas

This report is intended to be a one-stop-shopping primer that covers developments and implications in ten major emerging technology areas: AI, biotechnology and synthetic biology, cryptography, lasers, materials science, neuroscience, robotics, semiconductors, space, and sustainable energy technologies. The list is broad by design, and it includes fields that are widely regarded as pivotal to shaping society, economics, and geopolitics today and into the future.

That said, the ten major technology areas covered in this report are nowhere near an exhaustive catalogue of technology research areas at Stanford. And the list may change from year to year—not because a particular technology sputtered or because we got it wrong, but because categorizing technologies is inherently dynamic. Limiting this report to ten areas imposes discipline on what we cover and how deeply we go. We seek to highlight relationships among technologies in ways that may not be obvious: Quantum computing, for example, is an important field but does not have its own chapter. Instead, it is covered within the semiconductor chapter because we wanted to emphasize that even if quantum breakthroughs are realized, they will not address many important computing needs and challenges. Of note, nine of the ten technology chapters appearing in this edition are on the same subjects as in our previous report. In this report, we have combined nuclear energy and sustainable energy technologies into a single chapter and added a chapter on lasers.

Many of the most important issues cut across technological fields. We have expanded our previous report's crosscutting themes chapter to highlight fourteen of these themes and offer more examples and discussion. The themes include broad trends, like the tendency for technological breakthroughs to come in fits, starts, and lengthy plateaus that are extremely difficult even for leaders in those fields to predict. (AI leaders have experienced several so-called AI winters over decades as well as moments of profound and sudden progress like the 2022 release of ChatGPT.) They include enduring and widespread technological challenges like cybersecurity. And they include cognitive blind spots like frontier bias—the natural but mistaken assumption that the only transformational technologies sit on the frontiers of a field.

For each of the ten technology chapters, reviews of the field were led by world-renowned, tenured Stanford faculty members who also delivered seminars with other faculty discussants within and outside their areas of expertise. The SETR team also involved more than a dozen postdoctoral scholars and undergraduate research assistants who interviewed faculty across Stanford and drafted background materials.

Each technology chapter begins with an overview of the basics—the major technical subfields, concepts, and terms needed to understand how a technology works and could affect society. Next, we outline important developments and advances in the field. Finally, each chapter concludes by offering an over-the-horizon outlook that covers the most crucial considerations for policymakers over the next few years—including technical as well as policy, legal, and regulatory issues. The report ends with a chapter that looks across the ten technologies, offering analysis of implications for economic growth, national security, environmental and energy sustainability, human health, and civil society.

Three points bear highlighting. First, **we offer no specific policy recommendations in this report**. That is by design. Washington is littered with reports offering policy recommendations that were long forgotten, overtaken by events, or both. Opinions are plentiful. Expert insights based on leading research are not.

We aim to provide a reference resource that is both timeless and timely, an annual state-of-the-art guide that can inform successive generations of policymakers about how to think about evolving technological fields and their implications. Individual SETR faculty may well have views about what should be done. Some of us engage in policy writing and advising. But the mission of this collective report is informing, not advocating. We encourage readers interested in learning more about specific fields and policy ideas to contact our team at SETReview2025@stanford.edu.

Second, **SETR offers *a* view from Stanford, not *the* view from Stanford**. There is no single view of anything in a university. Faculty involved in this report may not agree with everything in it. Their colleagues would probably offer a different lay of the technology landscape with varying assessments about important developments and over-the-horizon issues. The report is intended to reflect the best collective judgment about the state of these ten fields—guided by leading experts in them.

Third, this report is intended to be the **introductory product that translates a broad swatch of technological research for nontechnical readers**. Other SETR offerings provide deeper dives into specific technological areas that should be of interest for subject-matter experts.

Ensuring continued American leadership in science and technology is essential, and it's a team effort. We hope this edition of the *Stanford Emerging Technology Review* continues to spark meaningful dialogue, better policy, and lasting impact. The promise of emerging technology is boundless if we have the foresight to understand it and the fortitude to embrace the challenges.

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Sources for key data points in this foreword and in the other sections of the publication can be found in the full version of the *Stanford Emerging Technology Review 2025*.

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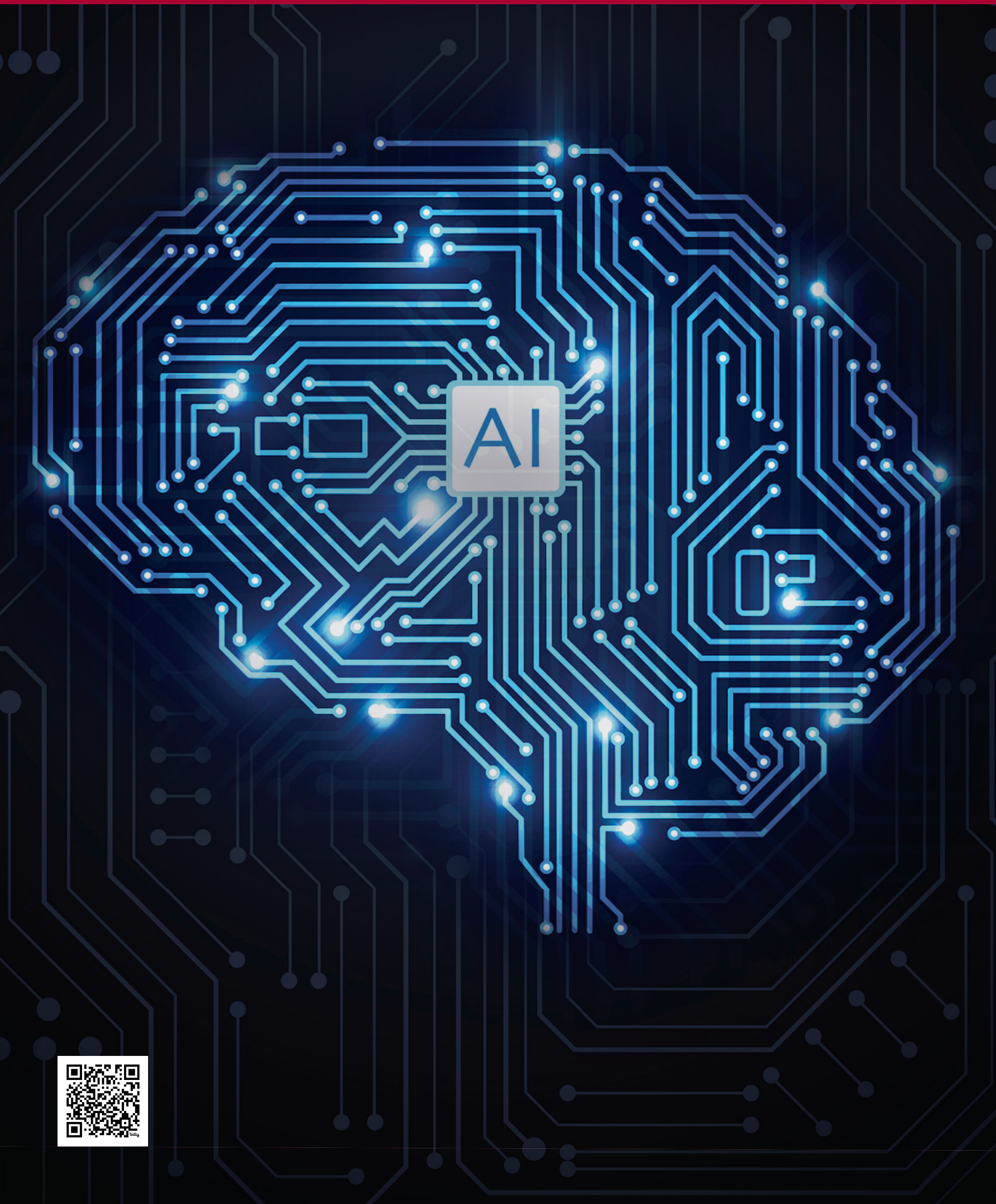
ARTIFICIAL INTELLIGENCE



KEY TAKEAWAYS

- Artificial intelligence (AI) is a foundational technology that is supercharging other scientific fields and, like electricity and the internet, has the potential to transform societies, economies, and politics worldwide.

- Despite rapid progress in the past several years, even the most advanced AI still has many failure modes that are unpredictable, not widely appreciated, not easily fixed, not explainable, and capable of leading to unintended consequences.

- Mandatory governance regimes for AI, even those to stave off catastrophic risks, will face stiff opposition from AI researchers and companies, but voluntary regimes calling for self-governance are more likely to gain support.

OVERVIEW

Artificial intelligence (AI) is the ability of computers to perform functions associated with the human brain, including perceiving, reasoning, learning, interacting, problem solving, and exercising creativity. AI promises to be a fundamental enabler of technological advancement and progress in many fields, arguably as important as electricity or the internet. In 2024, the Nobel Prizes for Physics and Chemistry were awarded for work intimately related to AI.

Three of the most important subfields of AI are computer vision, machine learning, and natural language processing. The boundaries between them are often fluid.

- **Computer vision (CV)** enables machines to recognize and understand visual information, convert pictures and videos into data, and make decisions based on the results.

- **Machine learning (ML)** enables computers to perform tasks without explicit instructions, often by generalizing from patterns in data. ML includes deep learning that relies on multilayered artificial neural networks to model and understand complex relationships within data.

- **Natural language processing (NLP)** equips machines with capabilities to understand, interpret, and produce spoken words and written texts.

Although AI draws on other subfields, it is mostly based on machine learning (ML), which requires data and computing power, often on an enormous scale. Data can take various forms, including text, images, videos, sensor readings, and more. The quality and quantity of data play a crucial role in determining the performance and capabilities of AI models. Models may generate inaccurate or biased outcomes, especially in the absence of sufficient high-quality data. Furthermore, the hardware costs of training leading AI models are substantial. Currently, only a select number of large US companies have the resources to build cutting-edge models from scratch.

KEY DEVELOPMENTS

Dominating the AI conversation in 2024 were foundation models, which are large-scale systems trained on very large volumes of diverse data. Such training endows them with broad capabilities, and they can apply knowledge learned in one context to a different context, making them more flexible and efficient than traditional task-specific models.

Large language models (LLMs) are the most familiar type of foundation model and are trained on very large amounts of text. LLMs are an example of generative AI, which can produce new material based on its training and the inputs it is given using statistical prediction about what other words are likely to be found immediately after the occurrence of certain words. These models generate linguistic output surprisingly similar to that of humans across a wide range of subjects, including computer code, poetry, legal case summaries, and medical advice. Specialized foundation models have also been developed in other modalities such as audio, video, and images.

Another key development is embodied AI. This integrates AI into robots to enhance their interactions with the physical world, enabling them to perform more complex tasks in fields like logistics and domestic assistance.

OVER THE HORIZON

AI Opportunities

AI users will not be limited to those with specialized training; instead, the average person will interact directly with sophisticated AI applications for a multitude of everyday activities. While AI can automate a wide range of tasks, it promises to enable people to do what they are best at doing. AI systems can work alongside humans, complementing and assisting them. Key sectors poised to take advantage of the technology include healthcare, agriculture, law, and logistics and transportation.

AI Risks

One challenge of implementing AI is managing the risks associated with the technology. Some of the known issues with leading AI models include:

- **Explainability** Today's AI is for the most part incapable of explaining how it arrives at a specific conclusion. Explanations are not always necessary, but in cases such as medical decision-making, they may be critical.

- **Bias and fairness** Machine learning models are trained on existing datasets, which means that any bias in the data can skew results.

- **Vulnerability to spoofing** For many AI models, data inputs can be tweaked to fool them into drawing false conclusions.

- **Deepfakes** AI provides the capability for generating highly realistic but entirely inauthentic audio and video, with concerning implications for courtroom evidence and political deception.

- **Overtrust** As trust in AI grows, the risk of overlooking errors, mishaps, and unforeseen incidents also increases.

- **Hallucinations** AI models can generate results or answers that seem plausible but are completely made up, incorrect, or both.

A second challenge is the future of work in an AI-enabled context. AI models have already demonstrated how they can be used in a wide variety of fields, including law, customer support, coding, and journalism, leading to concerns that the impact of AI on employment will be substantial, especially on jobs that involve knowledge work. In some cases, the technology will help workers to increase their productivity and job satisfaction. In others, AI will lead to job losses—and it is not yet clear what new jobs will arise to take their place.

POLICY, LEGAL & REGULATORY ISSUES

Research on foundational AI technologies is difficult to regulate, even among like-minded nations. It is even more difficult, and may well be impossible, to reach agreement between nations that regard each other as strategic competitors and adversaries. The same logic applies to voluntary restrictions on research by companies that compete with each other. Regulation of specific applications of AI may be more easily implemented, in part because of existing regulatory frameworks in domains such as healthcare, finance, and law.

Over the past couple of years, nations have explored possible governance regimes. In the United States, the president's Executive Order on the Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence was issued on October 30, 2023. In November 2023 and May 2024, the European Union and twenty-eight nations collectively endorsed international cooperation to manage risks associated with highly capable general-purpose AI models. The European Union's AI Act entered into force in August 2024.

BIOTECHNOLOGY AND SYNTHETIC BIOLOGY

KEY TAKEAWAYS

- Biotechnology is poised to emerge as a general-purpose technology by which anything bioengineers learn to encode in DNA can be grown whenever and wherever needed—essentially enabling the production of a wide range of products through biological processes across multiple sectors.
- The US government is still working to grasp the scale of this bio-opportunity and has relied too heavily on private-sector investment to support the foundational technology innovation needed to unlock and sustain progress.
- Biotechnology is one of the most important areas of technological competition between the United States and China, and China is investing considerably more resources. Lacking equivalent efforts domestically, the United States runs the risk of Sputnik-like strategic surprises in biotechnology.

OVERVIEW

Biotechnology partners with biology to create products and services, like engineering skin microbes to fight cancer or brewing medicines from yeast. This industry, already 5 percent of US GDP, is poised for significant growth. Synthetic biology, a subset of biotechnology focusing on enhancing living systems, relies on DNA sequencing and synthesis. DNA sequencers are machines that read or decode specific DNA molecules, while synthesizers write user-specified sequences of DNA. Rapid progress in these technologies is driving innovation and expanding biotechnology's potential applications.

Biology as a manufacturing process is distributed; leaves do not come from a central production facility but rather grow on trees everywhere. However, commercial biotechnology has become centralized and capital intensive. This contrast suggests a potential paradigm shift toward a more distributed approach in biotechnology, aligning it more closely with nature's decentralized production model.

Synthetic biology merges biology, engineering, and computer science to modify and create living systems, developing novel biological functions served by amino acids, proteins, and cells not found in nature. This field creates reusable biological "parts," streamlining design processes and reducing the need to start from scratch, thus advancing biotechnology's capabilities and efficiency.

Synthetic biology has applications in medicine, agriculture, manufacturing, and sustainability. DNA and RNA synthesis underlies all mRNA vaccines, including those for COVID-19. Synthetic biology can also cultivate drought-resistant crops and enable cells to be programmed to manufacture medicines or fuel on an agile, distributed basis.

KEY DEVELOPMENTS

Distributed biomanufacturing This offers unprecedented production flexibility in both location and timing. Fermentation production sites can be established anywhere with access to sugar and electricity. This approach enables swift responses to sudden demands like disease outbreaks requiring specific medications. Such adaptability revolutionizes manufacturing, making it more efficient and responsive to urgent needs.

Biology as a general-purpose technology Currently, biotechnology is used to make medicines, foods, and a narrow range of sustainable materials. But anything whose synthesis can be encoded in DNA could be grown. For example, some bacteria are capable of growing arrays of tiny magnets, and select sea sponges grow glass filaments similar to human-made fiber-optic cables. These and other examples suggest the potential for biology to be recognized as a general-purpose technology that could become the foundation of a more resilient manufacturing base.

Biological large language models (BioLLMs) Large language models (LLMs), which are a form of artificial intelligence, have emerged that are being trained on natural DNA, RNA, and protein sequences. Called BioLLMs, they can generate new biologically significant sequences that are helpful points of departure for designing useful proteins.

OVER THE HORIZON

To fully realize biology as a technology, improving biotechnology methods is essential. Advancing tools for measuring, modeling, and creating with biology offers a chance for global leadership. Similarly, streamlining and coordinating biotechnology workflows and commercialization can cement this position. Identifying gaps in national portfolios, such as the need for standards and reference materials to support a networked bioeconomy, is critical for strategic development.

The 2022 US federal strategic vision for biotechnology, including various initiatives and commissions, primarily focuses on applications and outcomes. However, these initiatives also provide opportunities to support foundational bioengineering research. Active multilateral efforts are needed to seize these chances through advice and input.

"Patient capital," both private and public, is crucial for foundational research, since many biotechnologies have long development timelines. Such long-term capital must be sustained in times of ebb and flow in the pace of scientific advancement. For example, although mRNA vaccines gained widespread public attention in 2021, their history began thirty years ago.

From a strategic perspective, four areas of significant consequence and opportunity need to be tracked: (1) progress toward constructing life from scratch (e.g., building a cell); (2) advances in electrobiosynthesis (i.e., growing biomass starting from renewable electricity and atmospheric carbon); (3) advances in next-generation DNA synthesis; and (4) progress toward profitability (i.e., when synthetic biology companies realize and sustain significant profits).

POLICY, LEGAL & REGULATORY ISSUES

Environmental and Safety Risks

Bioengineered organisms raise concerns about their potential impact on natural and human environments. For instance, bioengineered organisms that escape into the environment and possibly disrupt local food chains or natural species have long been an issue. Governments could improve public understanding of these risks and their management. Importantly, synthetic biology offers the potential to create organisms incapable of escaping or evolving, potentially addressing some of these concerns.

National Security and Public Safety Considerations

As the science and technology of synthetic biology become increasingly available to state and nonstate entities, legitimate fears arise that malicious actors will create organisms harmful to people and the environment. For example, polio, horsepox, SARS CoV-2, and influenza have been synthesized from scratch in laboratories.

The United States faces the challenge of maximizing biotechnology benefits while minimizing risks of misuse. In response, the National Security Commission on Emerging Biotechnology (NSCEB) and a Department of Defense task force have been established. Both are expected to produce significant reports during 2025, complementing ongoing Executive Office activities in shaping biotechnology policy and security measures.

Ethical Considerations

Different religions may have varying views on engineering new life forms and whether this violates their principles. These concerns, often classified as nonphysical impacts on innovation, are challenging to predict. A Wilson Center report notes that such issues involve potential harm to deeply held beliefs about what is right or good, including humans' relationship with themselves and nature.

CRYPTOGRAPHY

KEY TAKEAWAYS

- Cryptography is essential for protecting information, but alone it cannot secure cyberspace against all threats.
- Cryptography is the enabling technology of blockchain, which is the enabling technology of cryptocurrencies.
- Central bank digital currencies (CBDCs) are a particular type of cryptography-based digital currency supported by states and one that could enhance financial inclusion. Although the United States lags some countries in experimenting with a CBDC, it may benefit from a cautious, well-timed approach by learning from other nations' efforts.

OVERVIEW

Cryptography refers to the mathematics of protecting data from being surreptitiously altered or accessed inappropriately. It is essential for most internet activity, including messaging, e-commerce, and banking. There are two main types of cryptography: symmetric and asymmetric. Symmetric cryptography requires both parties to share one secret key to encrypt and decrypt data. In practice, sharing this secret key can be difficult. This led to the development of asymmetric encryption, which uses one public key, freely available to anyone, to encrypt data and a different private key to decrypt data. Hashing is another cryptographic method that generates a unique fixed-length string of numbers for a given input. Through the combination of hashing and other techniques, cryptography also enables identity verification and allows a recipient to confirm that a message was not altered in transit.

KEY DEVELOPMENTS

Blockchain

Blockchain technology employs cryptography to create a ledger that is secure and immutable. Each digital block in the blockchain contains a transaction and a cryptographic hash of the previous block, forming a chain. In this way, the blockchain is immutable, since changing earlier blocks would change the hashes and be easily detected. Blockchain technology has been applied to a variety of use cases:

- **Identity management** Blockchain securely stores a person's essential documents (like tax returns and health records), allowing selective data disclosure upon request. Applications are already emerging for identity management using blockchain.
- **Supply chain management** Blockchain offers a transparent way to track goods, their origins, and their quantities, benefiting industries with

authenticity concerns, including ones involving high-value products such as diamonds and other luxury goods.

- **Smart contracts** These are programmable self-executing contracts stored on the blockchain, eliminating the need for a third-party executor and increasing transaction efficiency.

- **Transactional records** Any kind of transactional record can be stored on a blockchain, thereby streamlining the process of buying and selling items by reducing fraud, increasing transparency, and cutting paperwork.

- **Cryptocurrencies** Digital currencies like Bitcoin and Ethereum use blockchain technology to create tokens that can act as a form of currency that does not have to be regulated or controlled by any central authority.

Secure Computation

Another important subfield of cryptography is secure computation, which enables multiple parties to contribute inputs to a function that they jointly compute without sharing their individual inputs with each other. Secure computation is extremely useful in financial and health settings where sharing individual client/patient data is unethical or even illegal.

Within secure computation are zero-knowledge proofs, which are cryptographic methods that allow one person to prove to someone else that he or she knows a specific piece of information without revealing to the other person any details about that information. The term "zero-knowledge" indicates that the receiver gains zero new knowledge about the information in question, apart from the fact that what the prover is saying is true. Zero-knowledge proofs have applications in banking, where a buyer may wish to prove to a seller the possession of sufficient funds for a transaction without revealing the exact amount of those funds. There are also applications ranging from cooperative tracking and verification of numbers of tactical nuclear warheads to checking provenance of digital images.

OVER THE HORIZON

There are a broad range of possibilities for cryptographically enabled data management services, but whether we will see their widespread deployment depends on complicated decisions about economic feasibility, costs, regulations, and ease of use. Misaligned incentives at companies (which have strong incentives to gather consumer data) and the difficulties of consumer and policymaker education present challenges to widespread adoption. Extensive deployment will also require would-be users to have confidence that proposed innovations will work as advertised. However, the mathematical and counterintuitive nature of cryptography concepts will make it challenging for policymakers, consumers, and regulators to place their trust in these applications.

Additionally, although cryptography is fundamentally a mathematical discipline, it relies on both human talent and computing power, with interdisciplinary centers advancing research through collaboration. Research can be funded by both the US government and private industry, but onerous proposal requirements make government funding far more difficult to achieve at present. As a result, research faculty prefer arrangements with the private sector, but only the US government is capable of funding research that may not pay off for many years.

POLICY, LEGAL & REGULATORY ISSUES

There has been no push to regulate basic research in cryptography for several decades. However, a number of aspects of the field do raise important policy issues:

- **Exceptional access (EA)** EA refers to a requirement that forces communications carriers and technology vendors to provide US law enforcement agencies access to encrypted information under specific legal conditions. Opponents argue that EA would inevitably weaken the security afforded by encryption to everyone, while supporters argue that the price of weakened security is worth the benefits to law enforcement.

- **Quantum computing** When realized, this novel form of computing is likely to pose a significant threat to today's public-key algorithms, and the US government has already initiated a transition to quantum-resistant ones. Continuing support for this transition is needed to protect sensitive information.

- **Cryptocurrencies** The lack of a regulatory framework for cryptocurrency often leaves many American users and investors confused about the basic workings of cryptocurrencies and their markets. It may also inadvertently incentivize entrepreneurs to move offshore.

- **A US central bank digital currency (CBDC)** CBDCs combine the convenience and lower costs of digital transactions with the regulatory oversight of traditional banking. While the United States is considering issuing its own CBDC, more than ninety other nations are currently researching, piloting, or rolling them out—including China with its deployment of the digital yuan. The development of CBDCs by other nations could reduce global dependence on the US dollar and on the largely US-controlled international financial infrastructure, thus undermining the effectiveness of US economic sanctions and other financial tools. America may lag China and some other countries with respect to introducing a CBDC, but implementation of a US CBDC could benefit from a cautious, well-timed approach by learning from earlier adopters' experiences.

LASERS

KEY TAKEAWAYS

- Laser technology has become essential for a wide range of applications, including communications, high-end chip production, defense, manufacturing, and medicine.
- Because advances in laser technology tend to occur in the context of specific applications, laser technology research and development is widely dispersed among different types of laboratories and facilities.
- Broad investment in next-generation lasers holds the potential to improve progress in nuclear fusion energy technology, weapons development, and quantum communication.

OVERVIEW

A laser is a light source with three important characteristics. Laser light is monochromatic, meaning the light is highly concentrated around a central wavelength, with very little emitted at other wavelengths. It is also directional—its energy can be concentrated into a small spot, significantly increasing intensity and making lasers useful for applications that require precision and high energy density, such as cutting, welding, and surgical procedures. Finally, it is coherent, which means that the light waves of the laser beam repeatedly reach the same peak or trough at the same point in time and space. This property is useful for laser-based measurement and sensing applications.

Lasers typically involve a power source (a pump), a gain medium (a material within which the energy supplied by the pump is turned into laser light), and a resonator that encloses the gain medium. Progress in laser technology depends on advancing one or more of these elements and is generally measured with respect to five technical characteristics of the beam: higher peak power, more energy in the beam, higher average power, shorter pulse lengths, and a wider range of wavelengths.

The engineering characteristics of lasers are also an important aspect of how fast the technology advances. For example, different configurations of power sources, resonators, and gain mediums can result in lasers of different size, weight, reliability, cost, and other key features. Addressing these and other engineering issues helps take lasers from labs to the commercial world, where many nonresearch applications make important use of them.

KEY DEVELOPMENTS

Improvements in laser technology since its invention in 1960 have allowed light to be manipulated and used in previously unimaginable ways. Lasers now underpin a huge range of scientific and industrial applications, including the following:

- **Military applications** Lasers serve a variety of ground-based missions, including attacking satellites and short-range air defense countering drones, rockets, artillery, and mortar rounds. An important advantage of lasers over conventional munitions in the latter role is a lower cost per shot and more rounds in their magazines (assuming their power supplies are not exhausted). An important disadvantage is that rain, fog, and smoke potentially limit a laser's range and beam quality.

- **Communications** Lasers can be used to transmit data between orbiting satellites. Compared to traditional radio transmission systems, laser communications allow for data-transfer rates that are 10 to 100 times faster. They are also more secure than radio systems because they have narrower beam widths that make transmissions harder to intercept.

- **Orbital debris removal** Lasers may be useful for removing debris from low Earth orbit. By firing a laser pulse at a piece of debris, it may be possible to force the debris to de-orbit and burn itself up as it passes through the atmosphere.

- **Imaging** Pulses from an X-ray free-electron laser (XFEL) can penetrate through materials to image structures and measure a material's physical properties. XFELs are particularly useful because the shorter wavelengths of X-rays allow better spatial resolution compared to visible light. In addition, they can emit very short pulses, which helps them excel at tracking changes over very short time periods.

- **Materials processing** Lasers can cut precise shapes, drill micron-scale holes, and deliberately deform surfaces to add stress to materials. Ultrashort-pulse lasers enable material to be ablated precisely with minimal damage to surrounding areas—a process useful in both manufacturing and surgery.

- **Chip fabrication** Lasers are used to generate a plasma, which is then stimulated to produce extreme ultraviolet (EUV) light to project a mask that carries circuit patterns onto wafers. Producing structures smaller than 2 nanometers on very-high-end chips relies completely on this technology, and these chips are critical for applications that demand high processing power, extremely energy-efficient operation, and miniaturization—requirements that characterize many systems of economic and national security importance.

OVER THE HORIZON

As critical components that are used across a very broad range of applications, lasers can be regarded as an enabling technology—one whose existence and characteristics enable applications that would not otherwise be feasible and/or affordable. Improving key laser parameters of operation—peak power, energy, average power, pulse length, and wavelength range—is a primary focus of extensive laser research, requiring novel approaches and techniques.

POLICY, LEGAL & REGULATORY ISSUES

Because lasers are an enabling technology for many applications, policy issues tend not to arise for the technology per se. Instead, they arise in the sectoral, societal, or policy context of a particular application. These issues can include technological maturity, cost-effectiveness, adequacy of the industrial base, dual-use considerations, and environmental and safety concerns.

For example, lasers as a defense against short-range ballistic projectiles appear to be technically feasible and cost-effective compared to missile interceptors, as laser shots cost only a few dollars each and missile interceptors cost tens or hundreds of thousands of dollars each. Environmental concerns ruled out certain laser technologies for such use, since the exhaust from those technologies was toxic.

A second example is lasers for surgery, which must address concerns about safety and cost-effectiveness. Safety guidelines for healthcare are constantly being updated and refined, as illustrated by a new standard issued in 2022 setting limits on the amount of light allowed to fall on a given surface area of the human body. In terms of cost, while some lasers for highly specific applications can still be very expensive, others that can be used for multiple applications are much cheaper.

MATERIALS SCIENCE

KEY TAKEAWAYS

- Materials science is a foundational technology that underlies advances in many other fields, including robotics, space, energy, and synthetic biology.
- Materials science will exploit artificial intelligence as another promising tool to predict new materials with new properties and identify novel uses for known materials.
- Future progress in materials science requires new funding mechanisms to more effectively transition from innovation to implementation and access to more computational power.

OVERVIEW

From semiconductors in computer chips to plastics in everyday objects, materials are everywhere. Knowing how to synthesize and process them, as well as understanding their structure and properties, has helped to shape the world around us. Materials science contributes to the development of stronger, lighter materials that improve everything from battery electrodes to medical implants and from automobiles to spacecraft.

Broadly speaking, materials science and engineering research focuses on four major activities. The first is the study of the structure of materials to understand how they are composed and organized from atomic to macroscopic scales. The second involves verifying the properties of materials, such as their conductivity, strength, and elasticity. The third area covers analysis and benchmarking of how materials perform in specific situations. The final one involves assessing how materials can be fabricated and manufactured.

KEY DEVELOPMENTS

- **Flexible electronics** involves the creation of electrical devices that can bend, stretch, and deform without compromising their performance. These can be used as wearable, skin-like devices. For instance, a "smart bandage" with integrated sensors to monitor wound conditions and provide electrical stimulation can cut the time needed to heal chronic wounds by 25 percent.
- **Additive manufacturing**, colloquially known as 3-D printing, is one of the most promising advances in materials processing over the past fifteen years. The technology comes in different forms. For instance, a method known as continuous liquid interface production (CLIP) uses directed ultraviolet light to form structures from a polymer resin.
- **Nanotechnology** exploits the properties of nanoscale materials (i.e., with one or more dimensions of 1–100 nanometers) that differ from the same materials in bulk—including electronic, optical, magnetic, thermal, and mechanical properties.

- **Quantum dots** are spherical nanocrystals that emit light and are used in television displays. They are a model example of a material whose properties vary because of its scale—in dot form, their optoelectronic properties differ from those of the same material when found in bulk. They can be used in areas such as medical imaging, solar cells, chemical and biological detection sensors, and anticounterfeiting measures.

The fundamental challenge of materials science as a discipline is the vast number of possible materials and material combinations that are possible and the associated time and cost involved in their synthesis and characterization (which is the general process by which materials' structure and properties are ascertained through spectroscopic, microscopic, and several other complementary methods).

Artificial intelligence (AI)—and, in particular, machine learning (ML)—offers promising solutions by leveraging experimental and computational data on the properties of materials. ML algorithms can recognize patterns in existing data and make generalized predictions about new materials. Their results provide a starting point for further exploration, but additional laboratory-derived data is needed to make ML-informed solutions more accurate, especially in the case of complex materials.

Another application of ML in materials science involves examining scientific literature for hidden relationships that could reveal latent knowledge about materials and point to new research directions. This approach has also been used to improve the design of electrolytes used in batteries and has been deployed in automated labs that can rapidly synthesize and characterize materials at scale.

OVER THE HORIZON

The materials research infrastructure today does not adequately support the transition from research to real-word applications at scale. Such transitions generally require launching a small-scale pilot project to demonstrate the feasibility of potential large-scale manufacturing. The reason pilots are necessary is that when the technology emerges from basic research, it is by definition too mature to qualify for research funding that is directed toward fundamental understanding but not mature enough to be commercialized by actual companies. However, neither government nor venture capital investors are particularly enthusiastic about financing pilot projects.

New funding vehicles are therefore needed to bridge this gap between bench-scale research and company-level investment. Such support could also establish national rapid prototyping centers, where academic researchers can find the help and tools necessary to build prototypes and pilot plants for their technology.

There is hope that ML-guided approaches will dramatically shorten the timescale for materials discovery and enable the design of materials optimized for specific applications. Continued development of both bottom-up computational approaches and top-down experimental data-driven methods will be needed to bridge the gap between fundamental material parameters and real-world device performance.

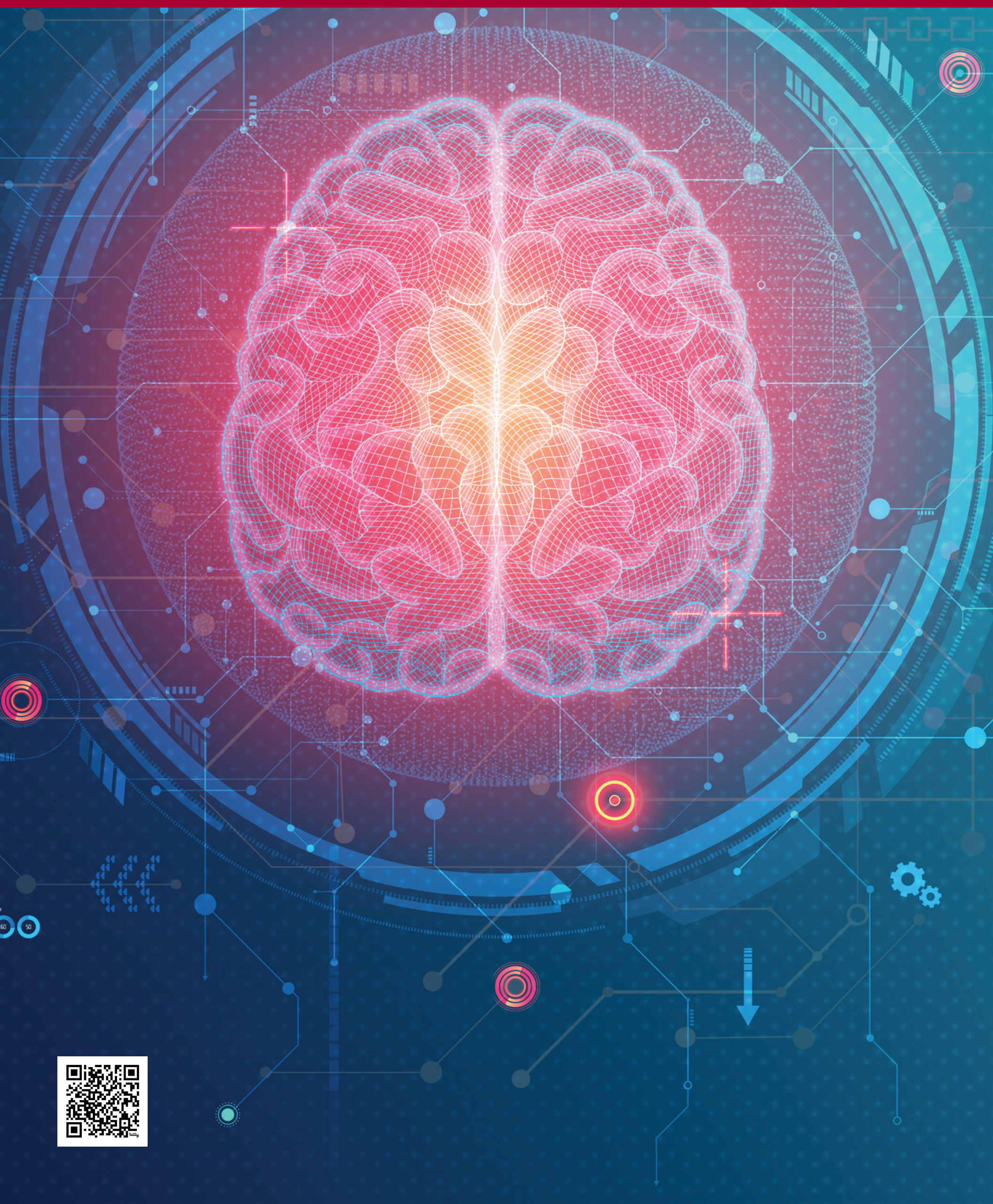
POLICY, LEGAL & REGULATORY ISSUES

- **Toxicity and environmental issues** As with regulation in other areas of technology, materials science faces concerns about balancing the need to ensure public safety with the imperative to innovate quickly. Nanoparticles raise particular concern because their small size may enable them to pass through various biological borders such as cell membranes. Multiple US government agencies currently oversee the regulation of and infrastructure for nanomaterials research.

- **Foreign collaboration and competition** Historically, the US has led the world in nanotechnology, but the gap between it and China has narrowed. As great-power competition intensifies, many researchers are concerned that fundamental research could now be subject to export controls, deterring international collaborations. There is an urgent need for clarification of these policies, particularly those delineating fundamental research and export-controlled research.

- **Infrastructure for ML-assisted materials science** The United States benefits from having some of the world's largest supercomputing resources, which are essential not only for ML but for developing extensive databases. However, better access to computing power—and to data—is needed to generate and analyze data effectively.

NEUROSCIENCE



KEY TAKEAWAYS

- Popular interest in neuroscience vastly exceeds the actual current scientific understanding of the brain, giving rise to overhyped claims in the public domain that revolutionary advances are just around the corner.
- Advances in human genetics and experimental neuroscience, along with computing and neuroscience theory, have led to some progress in several areas, including understanding and treating addiction and neurodegenerative diseases and designing brain-machine interfaces for restoring vision.
- American leadership is essential for establishing and upholding global norms about ethics and human subjects research in neuroscience, but this leadership is slipping with decreased strategic planning and increased foreign investments in the field.

OVERVIEW

Neuroscience is a multidisciplinary field of study that focuses on the components, functions, and dysfunctions of the human brain and our nervous system at every level. It reaches from the earliest stages of embryonic development to dysfunctions and degeneration later in life, and from the individual molecules that shape the functions of a neuron to the study of the complex system dynamics that are our thoughts and that dictate our behaviors.

Many practical applications could benefit from neuroscience research, including the development of treatments for neurological and psychiatric disorders such as epilepsy, learning disabilities, cerebral palsy, and anxiety, as well as Alzheimer's disease and other neurodegenerative disorders.

KEY DEVELOPMENTS

This report focuses on three research areas in neuroscience that show major promise for concrete applications: brain-machine interfaces (neuroengineering), degeneration and aging (neurohealth), and the science of addiction (neurodiscovery).

Neuroengineering

A brain-machine interface is a device that maps neural impulses from the brain and translates these signals to computers. The potential applications are wide-ranging: Augmenting vision, other senses, and physical mobility; direct mind-to-computer interfacing; and computer-assisted memory recall and cognition are all within the theoretical realms of possibility. However, headlines about mind-reading chip implants are still more in the realm of science fiction. Even with tremendous interest and rapid progress in neuroscience and engineering, the necessary theoretical understanding of how neurocircuits work is still limited to only a few areas of the brain. We also have not solved technical problems related to safely implanting electrodes in the brain.

Perhaps the most encouraging example of a brain-machine interface is the recent development of an artificial retina. People who have certain incurable retinal diseases are blind because the light-detecting cells do not work in their retinas, which convert light into corresponding electrical signals sent to the brain. To restore sight, the Stanford artificial retina project aims to take video images and use electrodes planted in the eye to simulate the electronic signals in a pattern that a functional retina would normally produce. Other brain-machine interfaces—such as one that translates brain activity controlling motor functions into signals that can be sent to an artificial prosthetic limb—are currently being developed, though they are less mature or less ambitious than the artificial retina project.

Neurohealth

Neurodegeneration is a major challenge as humans live longer. Diseases like Alzheimer's and Parkinson's surge in frequency with age. In the United States alone, the annual cost of Alzheimer's treatment is projected to soar from $305 billion today to $1 trillion by 2050. Alzheimer's disease is characterized by the accumulation of two different proteins—amyloid beta and tau—into toxic aggregates. As the brain regions where tau accumulates are those most cognitively impacted, a reasonable consensus exists that tau is the more direct cause of the neural death responsible for dementia.

Neurodiscovery

Understanding the science of the brain could also reveal the neural basis of addiction and chronic pain, which would be helpful in tackling the opioid epidemic by, for example, enabling new preventative therapies that alleviate significant drivers of opioid use. Neuroscience is also identifying brain mechanisms involved in relapse. This could help with finding effective treatments and identifying individuals who are more likely to relapse and are therefore in greater need of these therapies.

OVER THE HORIZON

While current treatments for Alzheimer's are less effective than would be desired given decades of research, there is reason for cautious optimism in the coming years. The potential for early detection prior to the onset of cognitive impairment is higher than it has ever been thanks to diagnostic tools that make it possible to cheaply test for biomarkers from blood plasma paired with more accurate but expensive spinal taps and positron emission topography, or PET, scans for toxic tau and amyloid beta buildup. In addition, new drugs are being tested that may actively slow cognitive decline in patients already exhibiting disease symptoms.

Neuroscience research could also help further develop brain-controlled artificial limbs and neural prostheses for seizure treatment. If a probe can be implanted into an area of the brain prone to seizures, it might be possible to predict the state of that area and warn of an imminent seizure. As understanding of the mathematics of our neural computations increases, these computational models may also influence the development of artificial intelligence (AI). For example, AI models typically require large amounts of data to train on, while humans can learn languages with a much smaller amount of training data. Better understanding the mathematical principles that define how brains compute may therefore improve AI.

POLICY, LEGAL & REGULATORY ISSUES

- Science fiction and fantastical headlines fuel belief that mind-reading technologies and other dystopias are imminent. The reality is that work to understand the human brain remains in its early stages. This vast gap between expectations and scientific reality leaves many open to dubious proclamations and pseudoscience.

- Over the past decade, much of the work described earlier has been funded by the United States government through the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative. However, the initiative's budget was cut by 40 percent in 2024, from $680 million to $402 million. Without additional financial support, neuroscience research in the US will decline just as other countries are investing more in the field.

- Neuroscience naturally raises many ethical concerns that merit careful, ongoing discussion and monitoring. Chief among these is research on human subjects. Ethical guidelines governing such research are usually national, not international. Managing differences in research regimes will be critical to harnessing the power of international collaboration.

ROBOTICS

KEY TAKEAWAYS

- Future robots may be useful for improving the US manufacturing base, reducing supply chain vulnerabilities, delivering eldercare, enhancing food production, tackling the housing shortage, improving energy sustainability, and performing almost any task involving physical presence.
- Progress in artificial intelligence holds the potential to advance robotics significantly but also raises ethical concerns that are essential to address, including the privacy of data used to train robots, data bias that could lead to physical harm by robots, and other safety issues.
- Achieving the full potential of robots will require a major push from the federal government and the private sector to improve robotics adoption and research across the nation.

OVERVIEW

In general, robots are human-made physical entities with ways of sensing themselves or the world around them and the ability to create physical effects on that world—beyond this statement, there is no consensus on the defining characteristics of a robot. Importantly, robots must integrate many different component technologies to combine perception of their environment with action. These technologies include actuators (e.g., motors, arms, gears), sensors, control systems, materials, power sources, and real-time programming. As a result, it takes a large interdisciplinary effort to move from a working prototype to a mass-produced robot in the market. The key engineering challenges in robotics are the design of individual components and the integration of these components to perform tasks.

Robots today are used primarily for tasks that fall within the "Three Ds": dull, dirty, or dangerous. These tasks include manufacturing lines, warehouse logistics, food production, disaster assistance, military services, security, and transportation. Autonomous robots excel at working in structured environments where conditions are predictable, whereas humans have the advantage in more unpredictable environments.

KEY DEVELOPMENTS

Some of the most important current influences on the robotics field include:

Manufacturing Robotics can help overcome some shortages in skilled labor in the manufacturing sector through automation and the development and increased deployment of collaborative robots, or cobots, that interact with human workers. New innovations such as robotic graspers that can handle even very fragile goods also make it easier to adapt and reconfigure production lines, reducing vulnerabilities in supply chains.

Instantaneous goods and services delivery Companies are deploying inventory as close as possible to customers so that goods and services are available very rapidly on demand. Robots are being used in multiple ways here. Drones and multiwheeled vehicles are being tested for conducting last-mile deliveries that get goods to customers, and remote robot-assisted surgery for certain conditions is increasingly available.

Food production Food production is predicted to increase by 50 percent by 2050, and in addition to boosting output farmers will also need to adapt to increasingly frequent adverse weather effects such as floods and droughts. Currently, robots are mainly deployed to reduce the cost of specific processes such as milking and seeding, but they can also increase agricultural efficiency and productivity by helping farmers collect data about the state of their crops using sensors, computer vision technology, and advanced algorithms.

OVER THE HORIZON

Artificial intelligence (AI) is set to play an increasingly important role in robotics by enabling robots to perform more complex tasks and facilitating greater autonomy. This will impact multiple fields such as healthcare and eldercare, where there is a huge dearth of qualified personnel. Assistive and rehabilitative robots are being developed and deployed to support caregivers. These robots can be electronic companions that help people with basic tasks associated with the activities of daily living both inside and outside their homes. They can also take the form of exoskeletons, which are wearable robotic devices that provide support with movement by, for instance, working with calf muscles to give people extra propulsion with each step taken.

The main challenge in healthcare and eldercare is the complexity of the tasks involved. Even a seemingly easy task like feeding a person can be hard for a robot because small movements of the individual can be hard to adjust for. AI and machine learning are being talked about as potential solutions to such issues, but for every new task a robot must learn, an immense amount of training data is required to ensure it will function safely.

As robots' capabilities advance, they will also play a bigger role in construction—where commercial robots are already capable of bricklaying, house framing, and moving heavy items on construction sites—and in the development and maintenance of sustainable energy infrastructure, where they are being used in tasks such as cleaning solar panels and maintaining wind turbines.

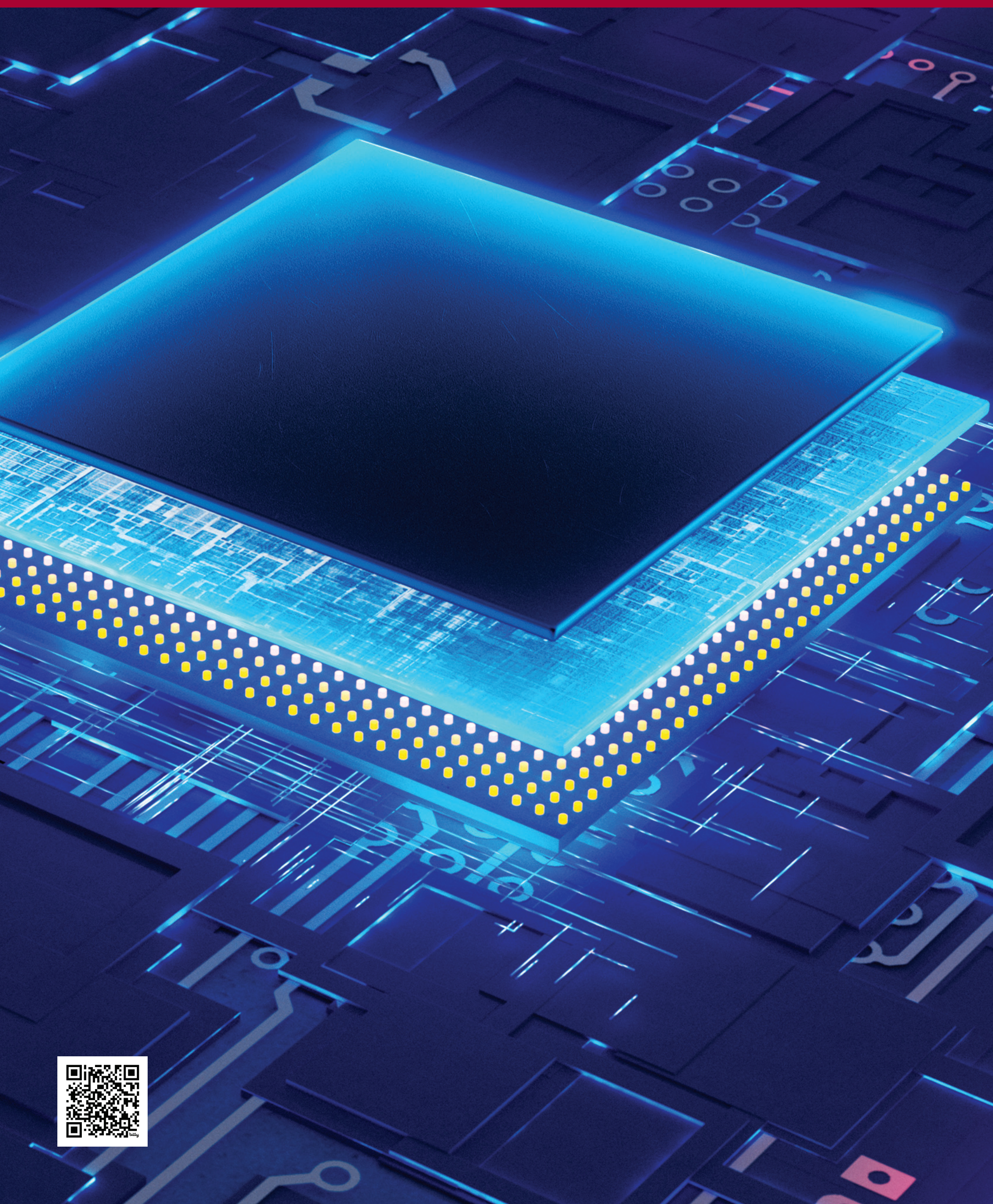
Achieving the full potential of robotics to help drive economic growth will require a major push from the federal government and the private sector to support research into robots and to encourage their use. Robot density in manufacturing in the United States in 2022 was 285 robots per ten thousand employees, ranking the country tenth in the world behind nations such as South Korea, Germany, and China. Advancing the use of robots will need to be balanced with a strategy to manage the transition carefully to avoid significant job displacement.

POLICY, LEGAL & REGULATORY ISSUES

These fall into three broad areas:

- **Privacy and consent** As noted earlier, large amounts of data will be needed to train robots, which will also collect significant volumes of data as they perform tasks. It will be important to think carefully about how to manage training data from a privacy and consent perspective, as well as the data gathered by robots in homes, hospitals, and other places they operate in.
- **Inclusion and integrity** These are crucial issues that concern both robotics and AI. For example, what if a robotic safety system scanning people infers that someone is carrying a gun because of their ethnicity? The consequences could be grave. Promoting norms and standards for robot-training datasets is essential to ensure that the diversity of America's population is properly reflected in them.
- **Safety** Setting standards for the safe performance of robotic systems is crucial for ensuring their successful and continued adoption. Cybersecurity standards for robots also need to be on a par with the domains they are used in, including healthcare and national security.

SEMICONDUCTORS



KEY TAKEAWAYS

- The growing demand for artificial intelligence and machine learning is driving innovations in chip fabrication that are essential for enhancing computational power and managing energy efficiency.
- Advances in memory technologies and high-bandwidth interconnects, including photonic links, are critical for meeting the increasing data needs of modern applications.
- Even if quantum computing advancements are realized, the United States will still need comprehensive innovation across the technology stack to continue to scale the power of information technology.

OVERVIEW

Semiconductors, often in the form of microchips, are crucial components in everything from smartphones and cars to advanced weapons and navigation systems used by the military. Chips must be designed and then subsequently manufactured in facilities known as "fabs" that can cost billions of dollars and take several years to build. Only a few companies, such as Intel, both design and make chips; most specialize in either design or manufacturing. In 2024, Taiwan Semiconductor Manufacturing Company (TSMC) controlled over 60 percent of the world's contract manufacturing and 90 percent of the manufacturing of advanced chips. With a large percentage of the world's chip factories located in Taiwan, the global supply chain for chips remains fragile.

KEY DEVELOPMENTS

For over half a century, a phenomenon known as Moore's law has governed developments in the semiconductor industry. This refers to a phenomenon that has seen the number of transistors on a chip of the same size and cost double roughly every couple of years, effectively doubling the chip's processing power. Moore's law is not a law of physics, but rather an observed trend driven by improvements in manufacturing tools and other factors that have been so consistent that everyone expects the cost of computing to keep decreasing with time. However, there are indications that Moore's law has slowed down and that its end may be in sight.

This is happening just as artificial intelligence (AI) and machine learning (ML) are driving a surge in demand for computing resources—and especially for specialized hardware such as advanced graphical processing units (GPUs) that power the development and training of many AI and ML models.

That shift is reshaping the semiconductor industry and emphasizing the need for novel computing advancements such as chiplets, 3-D heterogeneous integration, and silicon photonics. Chiplets are small, modular chips that specialize in specific functions and can be combined in ways that deliver more energy-efficient processing power than large, monolithic chips. 3-D heterogeneous integration is a semiconductor-manufacturing technique that vertically stacks different electronic components, such as processors and memory. Photonic interconnects that use photons to transmit data inside and between chips promise to enhance data-carrying capacity and reduce energy consumption compared with traditional interconnects that use electrons. Memory technology is also evolving and pushing the boundaries of what is possible to support data-intensive applications like AI.

Quantum computing remains a field of intense research and development, with significant progress being made in both the number and quality of quantum bits, or qubits, that can be generated and controlled. Quantum computers' promise lies in their potential to perform certain complex calculations at unprecedented speeds, which could have applications in fields such as cryptography, materials science, and complex system simulations.

Quantum computations are analogue, not digital, and current implementations can be disrupted by "noise" in the environment such as vibrations or changes in temperature, causing errors in calculations. Recent work in areas such as error-correcting algorithms has improved the fidelity of a modest number of qubits (around thirty), but far larger numbers of high-quality qubits—two or three orders of magnitude more—will be needed for the computers to become more broadly useful.

OVER THE HORIZON

Even if quantum computing does become mainstream, it will likely be useful for only a limited number of applications and won't replace today's semiconductor technology, which will need to keep evolving. As Moore's law reaches its limits, future improvements in computing will rely more on optimizing algorithms, hardware, and other technologies for specific applications rather than on general technology scaling. However, the industry faces a paradox: The need for radical innovation conflicts with the high costs and long timelines of chip development, which can reach over $100 million and take two years.

A potential avenue of progress calls for making it cheaper and easier to explore possible changes to system designs—in particular, by finding ways to ensure that specific changes to a chip do not require a complete redesign of it. Today, a full design overhaul is often required, which increases both the cost and the time needed to introduce changes. Solutions include enabling software designers to test custom accelerators without needing deep hardware knowledge, and creating new tools for application developers that enable them to make small hardware extensions to base platforms. The success of this approach depends on the willingness of major technology firms to participate in an app store–like model for hardware customization that balances open innovation with the profit motives of those companies. Broader innovation will also be needed, and to stimulate this the semiconductor industry will need to address the significant talent shortage it faces, particularly in the fields of hardware design and manufacturing.

POLICY, LEGAL & REGULATORY ISSUES

- Diversifying supply chains and further investing in domestic chip-manufacturing capacity is critical for mitigating geopolitical risks that are linked to the concentration of chip-manufacturing capacity in Taiwan.

- Initial steps have been taken by the United States with the passage of the Creating Helpful Incentives for Producing Semiconductors (CHIPS) and Science Act of 2022. This law earmarked $52.7 billion for semiconductor manufacturing, research, and workforce development, as well as tax credits to encourage private investment. Full implementation has not yet occurred, partly because not enough time has elapsed and partly because the appropriations the act called for have not been fully funded.

SPACE

KEY TAKEAWAYS

- A burgeoning "NewSpace" economy driven by private innovation and investment is transforming space launch, vehicles, communications, and key space actors in a domain that has until now been dominated by superpower governments.

- Space is a finite planetary resource. Because of dramatic increases in satellites, debris, and geopolitical space competition, new technologies and new international policy frameworks will be needed to prevent and manage international conflict in space and ensure responsible stewardship of this global commons.

- A race to establish a permanent human presence on the Moon is under way, with serious concerns that, despite Outer Space Treaty prohibitions against it, the first nation to reach the Moon may be in a strong position to prevent others from establishing their own lunar presence.

OVERVIEW

By definition, space technology is any technology developed for the purpose of conducting or supporting activities beyond the Kármán line (i.e., 100 kilometers, or 62 miles, above the Earth's surface).

Space systems can be crewed (e.g., the soon-to-be-decommissioned International Space Station [ISS], SpaceX Dragon) or uncrewed (e.g., telecommunication and navigation satellites). They also vary in size from large structures like the ISS (with a mass of 420 tons) to small and micro-satellites that can weigh less than 10 kilograms and are about the size of a loaf of bread. Today, a large majority of functional satellites in space weigh between 100 and 1,000 kilograms.

Space systems, particularly Earth-orbiting satellites, can also be characterized by the position of their orbits. Satellites are commonly positioned in low Earth orbit (LEO), medium Earth orbit (MEO), high elliptical orbit (HEO), or geosynchronous orbit (GEO). Space systems are also sometimes positioned around Lagrange points, or locations in space where a spacecraft can remain in a fixed spatial relationship to two bodies, such as the Sun and Earth, or Earth and the Moon.

KEY DEVELOPMENTS

One notable development in the space sector is the seismic shift from government-owned legacy systems to a "NewSpace" economy driven by private companies. While legacy systems are characterized by large, expensive spacecraft with long development timelines, new privatized space technologies are more accessible and less expensive.

In space transportation, private companies such as SpaceX, Rocket Lab, Blue Origin, and Virgin Galactic are making progress in providing reliable launches and developing new vehicles. SpaceX's Starship—the most powerful rocket ever built—could dramatically reduce the cost of achieving LEO orbits, aiming to make it 10 to 100 times less expensive than today. Meanwhile, Blue Origin, Voyager Space, and Axiom Space are developing commercial space stations to replace the ISS, which NASA plans to decommission in 2030. These new stations aim to ensure continued orbital research and expand human presence in space.

Governments are also complementing the capabilities of their remote sensing satellites, which rapidly gather extensive data about areas and objects of interest, with those of private companies in an effort to increase data resolution, reduce response times, and explore other valuable kinds of information. Ultimately, these data can be integrated to create a "digital twin" of Earth, enhancing the ability to predict, simulate, and respond to terrestrial phenomena.

As the "NewSpace" economy continues to grow, nations are embarking on a new "race to the Moon," which focuses on establishing a lunar presence for strategic and economic advantages. In 2023, India became the first nation to touch down near the lunar south pole—a prime target for settlement—and in 2024, China became the first nation to land on the Moon's far side.

OVER THE HORIZON

Future applications of space might include manufacturing of materials like pharmaceuticals, optics, and semiconductors; mining of the Moon and asteroids; harnessing of solar energy and beaming it to Earth; increased presence of military assets in space; and in-space logistics, servicing assembly, and manufacturing (ISAM) capabilities.

Although new space-based applications bring many benefits, they will contribute to an already growing number of objects in space. The number of active satellites alone rose from about one thousand in 2014 to around ten thousand in 2024, and there are around 170 million total pieces of debris larger than 1 millimeter in size in orbit. The risk of collision between these objects is growing, and such collisions can produce a cloud of debris that will remain in orbit and potentially threaten access to space. Ground-based stations are currently used to track space objects, but there is a push toward leveraging space-based sensors for more timely and accurate results.

The world faces a spaceflight sustainability paradox: The growing use of space to support sustainability and security on Earth will lead to more adverse impacts on the space environment itself. Even well-intentioned constellations of satellites, such as those used for remote sensing and object tracking, will contribute to greater space traffic challenges.

The proliferation of antisatellite weapons is also a major concern, as international disputes and tensions threaten the peaceful operation of satellites, space stations, and other space activities. To date, four nations have tested weapons capable of destroying or interfering with satellites in space: China, Russia, India, and the United States.

POLICY, LEGAL & REGULATORY ISSUES

- **Space governance** The release of NASA's strategy for sustainability in space activities in Earth orbit and the US Federal Communications Commission's issuance of its first-ever fine for improper satellite disposal from geostationary orbit are notable developments in space governance, but short-term policy advances must be unified with a longer-term vision to effectively address the responsible use of space.

- **Space traffic** New and consistent domestic and international policies are needed for tracking objects. Global transparency and coordination are essential, and the United States is well positioned to lead these efforts.

- **Eroding norms** Evidence suggests that international norms established in the Outer Space Treaty are eroding at the same time as nations are embarking on a new race to the Moon. Although the treaty prohibits claiming lunar sovereignty, there are concerns that nations might disregard it for national interests.

- **Dependence on the private sector** The US government's dependence on space capabilities provided by a very limited number of companies that are controlled by a single individual raises important policy questions of how to ensure that US space efforts align with US national interests.

SUSTAINABLE ENERGY TECHNOLOGIES

KEY TAKEAWAYS

- Although many clean energy technologies are now available and increasingly affordable, scaling them to a meaningful degree and building the massive infrastructure needed to deploy them will take decades.
- The largest impact on reducing emissions in the near to medium term will come from building a no- to very-low-emission electricity grid, electrifying passenger cars and small commercial vehicles, and transitioning residential and commercial heating and industrial energy.
- In the long term, technologies for decarbonizing buses and long-haul trucks, decarbonizing carbon-intensive industries, and reducing greenhouse gases from refrigerants and agriculture will play key roles in a net-zero, emissions-free energy infrastructure.

OVERVIEW

The transition to sustainable energy relies on improving every step of the energy supply chain, from generation to transmission to storage. However, the sheer scale of global energy has two major implications. First, no single technology or breakthrough can meet the world's demands for energy. Success will require a combination of approaches that bridge present sources, consumption, and infrastructure to a more sustainable future. Second, the imperative to deliver energy at scale unavoidably places an emphasis on cost. High-cost technologies, whether old or new and no matter how promising, cannot be deployed on a wide scale.

KEY DEVELOPMENTS

Substantial progress has been made in several sustainable energy technologies, including wind and solar generation of electricity; lower-loss long-distance transmission; lithium-ion (Li-ion) batteries for storing excess renewable energy produced when demand is low and for use in electric vehicles (EVs); efficient light-emitting diode (LED) lighting; and heat pumps for heating and cooling. But the widespread deployment of such technologies requires overcoming a variety of challenges, including a lack of sufficient public charging infrastructure for EVs, constraints in the raw materials supply chain to manufacture some of these technologies, and high up-front costs.

The technical feasibility of nuclear fission for generating electricity is well established. But many concerns related to economics and public acceptability remain to be overcome before the widespread deployment of fission reactors is possible. These include a legacy of significant cost overruns and construction delays; fuel security; manufacturing capability to build the hundreds of reactors that will be needed to meet the US goal of tripling nuclear-generated electricity by 2050; reactor safety; waste management; and nuclear weapons proliferation that might be prompted by widespread reactor deployments.

OVER THE HORIZON

Several important technologies await future refinement before they can be used on a large scale.

Energy Storage and Batteries

Energy storage is a core area of effort to make the energy grid more sustainable. Batteries have been the traditional way to capture and release electrical energy but are not yet sufficiently cost-effective for grid-scale storage. Long-duration energy-storage technologies like gravity, thermal, and mechanical storage aim to store energy without batteries, but scaling them remains a hurdle.

Batteries for long-duration energy storage need to be able to endure tens of thousands of capture-and-release cycles, retain charge over several hundreds of hours, and be made of inexpensive materials. Aqueous battery chemistries such as manganese-hydrogen batteries are more promising than Li-ion batteries from a cost perspective.

Renewable Fuels

Beyond storage, efforts are under way to deploy combustible fuels such as biodiesel and hydrogen that can be burned on demand but that are cleaner than traditional fossil fuels. Hydrogen, in particular, has been identified as a promising zero-carbon-emissions fuel source since its energy density by weight is three times that of fossil fuels. However, even in liquid or compressed-gas form (necessary for most transportation applications), hydrogen has a low energy density by volume—which means that a hydrogen fuel tank of a given size can carry much less energy than a gasoline fuel tank.

Finding cost-effective ways to produce hydrogen and carry it with acceptable leakage from production facilities to users is an additional challenge. Currently, it is sourced from fossil fuels through processes such as naphtha reforming, natural gas steam reforming, and coal gasification. Known as gray hydrogen, this conventional hydrogen has a significant carbon footprint and is not sustainable. Blue hydrogen, which is created from methane, and green hydrogen, which uses renewable electricity to generate hydrogen from water, are gaining attention because neither process emits greenhouse gases.

Carbon Capture and Removal

Carbon capture technologies work by capturing “new” carbon emissions produced by industrial processes or the burning of fossil fuels and then burying them, thereby preventing them from entering the atmosphere. Carbon removal refers to capturing “old,” or existing, carbon from the atmosphere. Both capture and removal are gaining research attention and could help users obtain some of the benefits of fossil fuels while minimizing carbon emissions.

Fusion

Fusion power continues to hold promise as a potentially limitless and inherently safe source of energy, but significant scientific and engineering breakthroughs are still needed to make it commercially viable. Commercial-scale fusion power plants are unlikely to play any important short-term role in reducing greenhouse gas emissions.

Grid Technologies

The future electric grid will be more extensive and complex than today's version, with distributed power generation, consumption, and storage. Power sources will be largely decentralized. As electrical demand rises, grid capacity must expand significantly, potentially doubling or tripling in size and necessitating substantial infrastructure upgrades to manage larger and more variable energy flows. The future development of a "smart grid," whose goal is to enhance efficiency, reliability, and resilience, will involve initiatives to replace old transmission lines with higher-performing ones, create vehicle-to-grid (V2G) systems that allow unused power from vehicle batteries to be fed to the grid, and deploy AI-driven energy systems to optimize grid operations and predict equipment failures.

POLICY, LEGAL & REGULATORY ISSUES

The most important policy issue related to sustainable energy is the need for a national consensus for continued support over the long term. For the next generation of emission-free technologies, America must sustain a stable innovation ecosystem over several decades.

A second major issue is the capability for manufacturing at scale—a capability the United States has largely lost. Because a meaningful energy transition depends on deployments at scale, promoting domestic production will be vitally important.

Third, policy must account for the harmful waste that even sustainable energy projects produce. Many forms of sustainable energy also require new acquisitions of land to build generating stations and storage facilities. Addressing these concerns proactively can minimize negative environmental impacts.

CROSSCUTTING THEMES

One of the most important and unusual hallmarks of this moment is convergence: Emerging technologies are intersecting and interacting in a host of ways, with important implications for policy. This report identifies fourteen themes and commonalities that cut across the technological areas featured in the *Stanford Emerging Technology Review*.

Category 1: Key Observations About How Technologies Evolve over Time

1. **Different risks arise from moving too fast and moving too slowly.** Moving too fast disrupts the status quo around which many national, organizational, and personal interests have coalesced, and may well lead to unintended consequences that give short shrift to security, safety, ethics, and geopolitics. Moving too slowly increases the likelihood that a nation may lose first-mover advantages in technology, economics, and national security.

2. **There is a trend toward increasing access to new technologies worldwide.** Even innovations that are US born are unlikely to remain in the exclusive control of American actors for long periods.

3. **The synergies between different technologies are large and growing.** Advances in one technology often support advances in other technologies.

4. **The path from research to application is rarely linear.** Some innovations arise through a step-by-step progression from basic research to applied research to development to prototyping and finally to marketable products. But not all. Many scientific developments enhance understanding but never advance to the marketplace. Many marketable products emerge in nonlinear fashion, typically after numerous rounds of feedback between phases. Other products emerge only when several different technologies acquire maturity.

5. **The speed of change is hard to anticipate, even for leading researchers.** Technology often progresses in fits and starts, with long periods of incremental results followed by sudden breakthroughs.

6. **Nontechnical factors often determine whether new technologies succeed or fail.** Adoption of new technologies hinges on economic viability and societal acceptability, not just scientific proof-of-concept and engineering feasibility.

7. **The US government is no longer the main driver of technological innovation.** While it has historically funded advances like semiconductors and the internet, today the private sector leads R&D investment, raising concerns about ensuring that national interests are protected and maintaining strong support for basic science, which is vital for future innovation.

8. **Technological innovation occurs in both democracies and autocracies, but different regime types enjoy different advantages and challenges.** Democracies provide greater freedom for exploration while authoritarian regimes can direct sustained funding and focus to key technologies.

Category 2: Common Innovation Enablers and Inhibitors

1. **Human talent is essential for scientific discovery but cannot be manufactured at will.** It must be domestically nurtured or imported from abroad, and both of these alternatives face challenges. Better pathways to permanent residence for STEM doctoral graduates on student visas would help the United States to retain talent that would otherwise leave the country. Strengthening the domestic pipeline of STEM workers is also essential.

2. **A bias toward frontier science and technology often overestimates benefits, at least in the short term.** Analysts and policymakers frequently focus on recent innovations, overlooking innovation with older technologies that could still be transformative.

3. **Good public policy anticipates varying perspectives on technology—optimism, pessimism, and realism.** Technological optimists often dismiss early concerns about risks as stifling innovation, but downsides inevitably emerge at scale. By seeking out voices highlighting potential risks early, policymakers can create more-balanced policies that foster innovation while minimizing negative impacts.

4. **US universities play a critical but often underappreciated role in the innovation ecosystem.** Unlike for-profit research enterprises, they are the only organizations with the mission of pursuing high-risk research that may not pay off commercially for a long time. That high-risk focus has yielded high-benefit payoffs in a wide range of fields.

5. **Sustaining American innovation requires long-term government R&D.** Investments with clear strategies and sustained priorities are crucial, not policies that result in the increasingly common wild swings being seen from year to year.

6. **Cybersecurity is an enduring concern for every aspect of emerging technology research.** State and nonstate actors will continue to threaten the confidentiality, integrity, and availability of information that is crucial for emerging-technology research and development.

FACULTY COUNCIL ADVISORS

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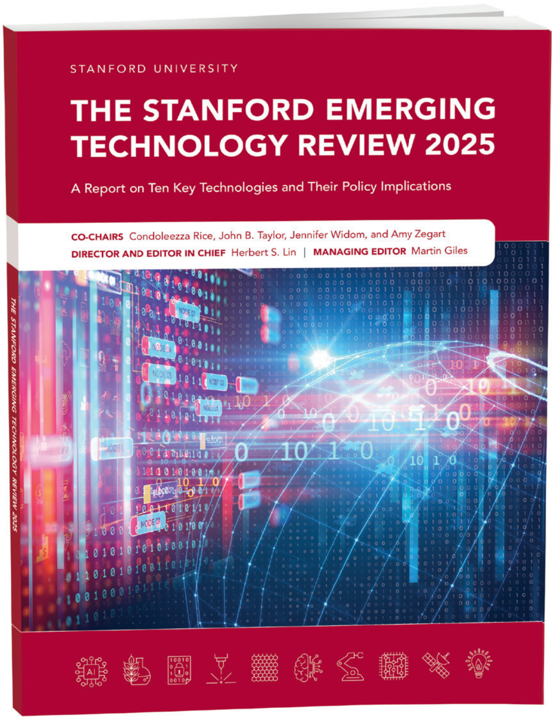

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