STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2023

A Report on Ten Key Technologies and Their Policy Implications

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EXECUTIVE SUMMARY

Emerging technologies have never been more important or difficult to understand. Breakthrough advances seem to be everywhere, from ChatGPT to the COVID-19 mRNA vaccines to constellations of cheap commercial shoebox-size satellites that can track events on Earth in near-real time. This is a pivotal technological moment offering both tremendous promise and unprecedented challenges. Policymakers need better expert resources to help them more easily understand the burgeoning and complex array of technological developments—more easily and more continuously.

The *Stanford Emerging Technology Review* is designed to meet this need, offering an easy-to-use reference tool that harnesses the expertise of Stanford University's leading science and engineering faculty in ten major technological areas:

***SETR* 2023 Focus Technologies**

Artificial Intelligence
Biotechnology and Synthetic Biology
Cryptography
Materials Science
Neuroscience
Nuclear Technologies
Robotics
Semiconductors
Space
Sustainable Energy Technologies

These particular fields were chosen for the 2023 report because they leverage areas of deep expertise at Stanford and cover many critical and emerging technologies identified last year by the Office of Science and Technology Policy in the White House and other US government departments. However, *SETR* focus technologies are likely to change over time, not because anyone "got it wrong," but because science and technology never sleep, the borders between fields are porous, and different people categorize similar research in different ways.

Report Design

This report is organized principally by technology, with each area covered in a standalone chapter that gives an overview of the field, highlights key developments, and offers an over-the-horizon view of important technological and policy considerations. Although these chapters can be read individually, 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. We examine these broader dynamics in chapters 11 and 12. In chapter 11, we describe a number of themes and commonalities that cut across many of the technologies we describe earlier in the report. In chapter 12, we consolidate technological developments across all ten areas and discuss how they apply to five policy areas: economic growth, national security, environmental and energy sustainability, health and medicine, and civil society.

Three tensions run throughout and are worth keeping in mind.

1. Timeliness and timelessness Each chapter seeks to strike a balance between covering recent developments in science and in the headlines and providing essential knowledge about how a field works, what is most important, and what challenges lie ahead.

2. Technical depth and breadth This report intentionally skews toward breadth, offering a 30,000-foot view of a vast technological landscape in one compendium. Readers should consider this report as an introductory course. *SETR* will issue deeper-dive reports and other educational tools in the months ahead that will offer more advanced examinations of each field.

3. Technical and nontechnical aspects of innovation We start with the science but do not end with the science. Technological breakthroughs are necessary but not sufficient conditions for successful innovation. Economic, political, and societal factors play enormous and often hidden roles. Johannes Gutenberg invented the printing press in 1452, but it took more than 150 years before the Dutch invented the first successful newspapers—not because they perfected the mechanics of movable type, but because they decided to use less paper, making newspapers sustainably profitable for the first time.[1] Each chapter in this report was written with an eye toward highlighting important economic, political, policy, legal, and societal factors likely to impede, shape, or accelerate progress.

Technologies and Takeaways at a Glance

Artificial Intelligence (AI)

AI is a computer's ability to perform some of the functions associated with the human brain, including perceiving, reasoning, learning, interacting, problem solving, and even exercising creativity. In the last year, the main AI-related headline was the rise of large language models (LLMs) like GPT-4, on which the chatbot ChatGPT is based.

KEY CHAPTER TAKEAWAYS:

- AI is a foundational technology that is advancing other scientific fields and, like electricity and the internet, has the potential to transform how society operates.
- Even the most advanced AI has many failure modes that are unpredictable, not widely acknowledged, not easily fixed, not explainable, and capable of leading to unintended consequences.
- There is substantial debate among AI experts about whether AI poses a long-term existential risk to humans, and whether the most important risks are current weaknesses of AI.

Biotechnology and Synthetic Biology

Biotechnology is the use of cellular and biomolecular processes to develop products or services. Synthetic biology is a subset of biotechnology that involves using engineering tools to modify or create biological functions—like creating a bacterium that can glow in the presence of explosives. Synthetic biology is what created the COVID-19 mRNA vaccine in record time—although it relied on decades of earlier research. Just as rockets enabled humans to overcome the constraints of gravity to explore the universe, synthetic biology is enabling humans to overcome the constraints of lineage to develop new living organisms.

KEY CHAPTER TAKEAWAYS:

- Biotechnology is burgeoning, contributing around 5 percent to US GDP with a historical doubling time of about seven years.
- Synthetic biology is third-generation biotechnology, complementing domestication and breeding (the first generation) and gene editing (the second generation).
- The United States is struggling to grasp the scale of the bio-opportunity, the strategic ramifications unique to network-enabled biotechnologies, and the possibilities and perils of distributed biomanufacturing.

Cryptography

The word *cryptography* originates from Greek words that mean "secret writing." In ancient times, cryptography involved the use of ciphers and secret codes. Today, it relies on sophisticated mathematical models to protect data from being altered or accessed inappropriately. Cryptography is often invisible, but it is essential for most internet activities, such as messaging, e-commerce, and banking. In recent years, a type of cryptographic technology called blockchain—which records transactions in distributed ledgers in the computing cloud that cannot be altered retroactively without being detected—has been used for a variety of applications, including time-stamping and ensuring the provenance of information, identity management, supply chain management, and cryptocurrencies.

KEY CHAPTER TAKEAWAYS:

- Cryptography is essential for protecting information but will never be enough to secure cyberspace.
- Cryptocurrencies have received a great deal of media attention, but they are not the most important issue in cryptography today.
- Cryptocurrencies use blockchain technology, but they are not the same; blockchain has many other important and promising applications.

Materials Science

Materials science studies the structure and properties of materials—from those visible to the naked eye to microscopic features—and how they can be engineered to change performance. Materials science contributions have led to better semiconductors, "smart bandages" with integrated sensors and simulators that can accelerate healing, more easily recyclable plastics, more energy efficient and flexible solar cells, and stronger aircraft parts.

KEY CHAPTER 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 AI as another promising tool to predict new materials with new properties and identify novel uses for known materials.
- The structure of funding in materials science does not effectively enable transition from innovation to implementation. Materials-based technology that has been thoroughly tested at the bench scale may be too mature to qualify for basic research funding (because the high-level basic science is understood) but not mature enough to be directly commercialized by companies.

Neuroscience

Neuroscience is the study of the human brain and the nervous system—its structure, function, healthy and diseased states, and life cycle from embryonic development to degeneration in later years. The brain is perhaps the least understood and yet most important organ in the human body. Three major research subfields of neuroscience are neuroengineering (e.g., brain-machine interfaces), neurohealth (e.g., brain degeneration and aging), and neurodiscovery (e.g., the science of addiction).

KEY CHAPTER 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 computing have led to progress in several areas, including understanding and treating addiction and neurodegenerative diseases, and designing brain-machine interfaces.
- American leadership is essential for establishing and upholding global norms about ethics and human subjects research in neuroscience.

Nuclear Technologies

Nuclear technologies involve producing energy with potential applications for electricity generation, medicine, and weapons. There are two major nuclear processes: (1) fission, which is the process of splitting the nucleus of a particular type of element; and (2) fusion, which produces energy by causing two atoms to collide and fuse together. Nuclear power plants have used controlled fission chain reactions for decades. In the past year, however, Lawrence Livermore National Laboratory achieved a milestone breakthrough, raising hopes that fusion might someday be controlled to drive electrical generators without the long-lasting radioactive waste that fission produces.

KEY CHAPTER TAKEAWAYS:

- Nuclear fission offers a promising carbon-free power source that is already in use but faces safety and proliferation concerns, economic obstacles, and significant policy challenges to address long-term radioactive waste disposal.
- Nuclear fusion recently achieved an important milestone by demonstrating energy gain in the laboratory for the first time. However, further research breakthroughs must be achieved in the coming decades before fusion can be technically viable as an energy alternative.
- Many believe that small modular reactors (SMRs) are the most promising way to proceed with nuclear power, but some nuclear experts have noted that SMRs do not solve the radioactive waste disposal problem.

Robotics

Robotics is an integrative field that draws on advances in multiple technologies rather than a single discipline. "What is a robot?" is a harder question to answer than it appears. At a minimum, the emerging consensus among researchers is that a robot is a physical entity that has ways of sensing itself and the world around it and can create physical effects on that world. Robots are already used across a range of sectors in a variety of ways—including assembly line manufacturing, space exploration, autonomous vehicles, tele-operated surgery, military reconnaissance, and disaster assistance.

KEY CHAPTER TAKEAWAYS:

- Although robots today are mostly used for the Three Ds (dull, dirty, or dangerous tasks), in the future they could be used for almost any task involving physical presence, because of recent advances in AI, decreasing costs of mobile component technologies (e.g., cameras in smartphones), and designs enabled by new materials and structures.
- Robotics has and will transform many industries through elimination, modification, or creation of jobs and functions.

- Understanding and communicating how robots will affect people's lives directly in their physical spaces (e.g., security robots in malls) as well as more existentially (e.g., transitioning jobs like truck driving from human-driven to autonomous vehicles) will shape how the United States accepts and benefits from robotic technologies.

Semiconductors

Semiconductors, or chips, are crucial and ubiquitous components used in everything from refrigerators and toys to smartphones, cars, computers, and fighter jets. Chip production involves two distinct steps: (1) *design*, which requires talented engineers to design complex integrated circuits involving millions of components; and (2) *fabrication*, which is the task of actually manufacturing chips in large, specially designed factories called "fabs." Because fabs involve highly specialized equipment and facilities—the "clean rooms" in which chips are made require air that is one thousand times more particle-free than a hospital operating room—they are extremely expensive to build and require expertise to operate. US companies still play a leading role in semiconductor design, but US semiconductor-manufacturing capacity has plummeted and now lags dangerously behind Taiwan Semiconductor Manufacturing Company (TSMC) and Korea's Samsung. The Creating Helpful Incentives to Produce Semiconductors and Science Act of 2022 (CHIPS Act of 2022) was intended to help the US semiconductor industry regain a foothold in fabrication, but progress is expected to take years, if not decades. Because of the cost and complexity involved, success remains uncertain. At the same time, we are reaching the limits of exponential technical and cost improvements in the chip fabrication process, known as Moore's law. Until now, systems and software have been designed with the expectation that semiconductor capabilities would dramatically increase and costs would decrease over time. That is unlikely to be the case in the future, with profound implications for the development of hardware and software as well as the innovation that depends on it.

KEY CHAPTER TAKEAWAYS:

- Moore's law, which for fifty years has predicted rapid increases in semiconductor capabilities at decreasing costs, is now ending, raising profound implications for the future of hardware and software development.

- Recent research has identified methods that allow innovations in materials, devices, fabrication, and hardware to be added to existing process or systems at low incremental cost. These methods need to be further developed since they will be essential to continue to improve the computing infrastructure we all depend on.

- Quantum computing may solve certain specialized problems, but experts debate whether it can ever achieve the rapid, consistent, predictable performance growth that semiconductors have enjoyed.

Space

Space technologies include any technology developed to conduct or support activities approximately sixty miles or more beyond Earth's atmosphere. A single space mission is a "system of systems"—including everything from the spacecraft itself to propulsion, data storage and processing, electrical power generation and distribution, thermal control to ensure that components are within their operational and survival limits, and ground stations. While in the past space was the exclusive province of government spy satellites and discovery missions, the number and capabilities of commercial satellites have increased dramatically in recent years. Today, more than eight thousand working satellites circle the planet, many no larger than a loaf of bread. Some operate in constellations that can revisit the same location multiple times a day and offer image resolutions so sharp they can identify different car models driving on a road.

KEY CHAPTER TAKEAWAYS:

- Space technologies are increasingly critical to everyday life (e.g., GPS navigation, banking, missile defense, internet access, and remote sensing).
- Space is a finite planetary resource. Dramatic increases in satellites, debris, and competition are threatening access to this global commons.
- Private-sector actors play a critical and growing role in many aspects of space-based activities (e.g., launch, vehicles, and communications), because they offer better, cheaper, and rapidly deployable capabilities.

Sustainable Energy Technologies

This vital strategic resource for nations generally involves generation, transmission, and storage. In recent years it has also come to include carbon capture and carbon's removal from the atmosphere. Energy mix and innovation are key to efforts to address climate change.

KEY CHAPTER TAKEAWAYS:

- The most significant challenge to achieving sustainable energy is scale. Countries will need to source, manufacture, and deploy massive generation, transmission, and storage capabilities to meet global energy needs.
- Because global energy needs are vast, no single technology or breakthrough will be enough.
- Over-the-horizon challenges include decentralizing and modernizing the country's electricity grids and achieving greater national consensus about energy goals to enable strategic and effective R&D programs and funding.

Important Crosscutting Themes

Chapter 11 discusses twelve themes that cut across the technological areas. These are:

1. Different risks arise from moving too fast and moving too slowly. Innovation that emerges too fast threatens to disrupt the status quo around which many national, organizational, and personal interests have coalesced. It is also more likely to lead to unintended consequences and give short shrift to security, safety, ethics, and geopolitics. Innovation that moves too slowly increases the likelihood that a nation will lose the technical, economic, and national security advantages that often accrue to first movers in a field.

2. Ideas and human talent play a central role in scientific discovery and cannot be manufactured at will. They must be either domestically nurtured or imported from abroad. Today, both paths for generating ideas and human talent face serious and rising challenges.

3. The US government is no longer the primary driver of technological innovation or funder of research and development. Historically, technological advances (e.g., semiconductors, the internet, jet engines) were funded and advocated by the US government. Today, private sector R&D investment is playing a much larger role, raising important concerns about how to ensure that the national interest is well considered and that basic science—which is an important foundation for future innovation—remains strong.

4. 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.

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

6. The path from research to application is often not linear. Many believe that technological breakthroughs arise from a step-by-step linear progression where basic research leads to applied research, which then leads to development and prototyping and finally to a marketable product. Yet innovation often does not work this way. Many scientific developments enhance understanding but never advance to the marketplace. Many marketable products emerge in nonlinear fashion, after many rounds of feedback *between* phases. Other products emerge only when several different technologies acquire maturity.

7. 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 on the technologies they believe are most important.

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

9. 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.

10. US universities play a pivotal role in the innovation ecosystem that is increasingly at risk. Although the US government frequently talks about the importance of public-private partnerships in emerging technology, universities also play a pivotal and often underappreciated role. They are the only organizations with the mission of pursuing high-risk research that may not pay off commercially for a long time, if ever. That high-risk focus has yielded high-benefit payoffs in a wide range of fields.

11. Sustaining American innovation requires long-term government R&D. Investments with clear strategies and sustained priorities are crucial, not the increasingly common wild swings from year to year.

12. 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.

Finally, each of the ten technology fields covered in this report bears on five policy areas that are of interest to policymakers: economic growth, national security, environmental and energy sustainability, health and medicine, and civil society. Chapter 12 identifies applications and consequences of each field as they apply to these policy areas.

NOTES

1. Andrew Pettegree and Arthur der Weduwen, *The Bookshop of the World: Making and Trading Books in the Dutch Golden Age* (New Haven, CT: Yale University Press, 2019), 70–72.