STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2023

A Report on Ten Key Technologies and Their Policy Implications

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FOREWORD

Emerging technologies are transforming societies, economies, and geopolitics. This moment brings unparalleled promise and novel risks. In every era, technological advances buoy nations that develop and scale them—helping to save lives, win wars, foster greater prosperity, and advance the human condition. At the same time, history is filled with examples where slow-moving governments stifled innovation in ways policymakers never intended, and nefarious actors used technological advances in ways that inventors never imagined. Technology is a tool. It is not inherently good or bad. But its use can amplify human talent or degrade it, uplift societies or repress them, solve vexing challenges or exacerbate them. These effects are sometimes deliberate but often accidental.

The stakes of technological developments today are especially high. Artificial intelligence (AI) is already revolutionizing industries, from music to medicine to the military, and its impact has been likened to the invention of electricity. Yet AI is just one among many technologies that are ushering in profound change. Fields like synthetic biology, materials science, and neuroscience hold potential to vastly improve health care, environmental sustainability, economic growth, and more. We have experienced moments of major technological change before. But we have never experienced the convergence of so many technologies with the potential to change so much, so fast.

The *Stanford Emerging Technology Review* (*SETR*) is the first product of a major new Stanford technology education initiative for policymakers. Our goal is to help both the public and private sectors better understand the technologies poised to transform our world so that the United States can seize opportunities, mitigate risks, and ensure that the American innovation ecosystem continues to thrive.

Our efforts are guided by four observations:

1. **Policymakers need better resources to help them understand technological developments faster, continuously, and more easily**

Technology policy increasingly requires a more sophisticated understanding across a broad range of fields and sectors. Indeed, policymakers today include an expanding array of decision makers, from legislators and executive branch officials in Washington to state and local governments, investors, and corporate leaders. Too often, government leaders lack technical expertise to understand scientific developments, while technologists lack the policy expertise to consider and build security, safety, and other societal considerations into their products by design. Key takeaways of this report, for example, include the following findings that may be surprising and even counterintuitive to nonexperts:

- Artificial intelligence has received a great deal of media attention, but biotechnology could ultimately be as transformational to society as computing.

- Space technologies are increasingly critical to everyday life, from GPS navigation to banking. But space is a planetary resource that is rapidly becoming congested and contested—with thousands of new commercial satellites and an estimated million pieces of space debris that could threaten access to these global commons.

- The most significant challenge to achieving sustainable energy is scale; simply providing a 72-hour supply of backup energy worldwide would take two hundred years of lithium-ion battery production.

- Cryptocurrencies are not the most important issue in cryptography today, and they are not synonymous with blockchain, which has widespread applications.

As these examples suggest, policymakers need better, easy-access resources to help them understand technological basics and new discoveries before crises emerge; to focus their attention on the most important issues; to better assess the policy implications; and to see over the horizon to shape, accelerate, and guide future technological innovation and applications. We need a new model of technology education for nontechnical leaders. This report aims to be a first, important step.

2. 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, for example, 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.

3. Academia's role in American innovation is essential yet increasingly at risk

The US innovation ecosystem has three pillars: the government, the private sector, and the academy. Success requires that all three remain robust and

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actively engaged. Throughout history, America's research universities have generated transformational scientific discoveries, from the invention of the polio vaccine to rocket fuel. Universities have also been the seedbeds of policy innovations, from nuclear deterrence theory to behavioral economics. And they have played a vital role in training the next generation.

Today, however, innovations are increasingly emerging from the private sector, often alongside academia. The funding sources for innovation have shifted, too—in deeply worrying ways. The US government is the only funder capable of making large and risky investments in the basic science conducted at universities (and national laboratories) that is essential for future applications. Yet federal research and development (R&D) funding has plummeted since the 1960s, from 1.86 percent of GDP in 1964 to just 0.66 percent of GDP in 2016.[1] Although private sector investment in technology companies and associated university research has increased substantially, it is no substitute; federal funding of university research leads universities to study different technological challenges and opportunities than industry funding does. As a Council on Foreign Relations innovation task force report concluded:

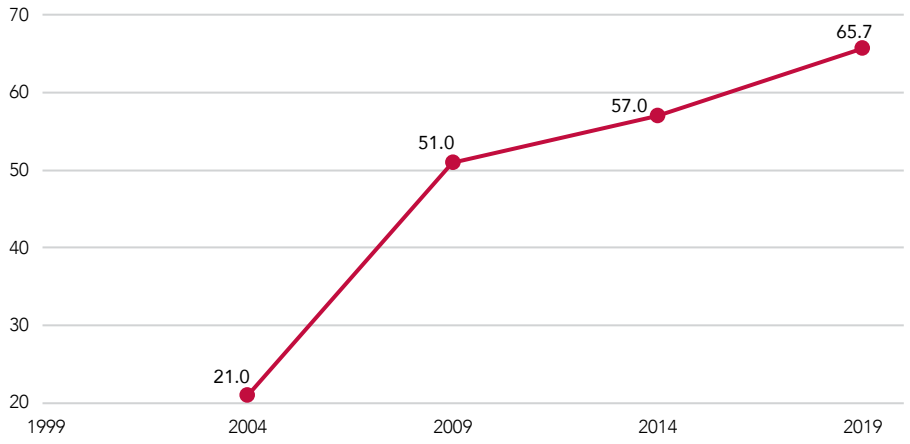
> U.S. leadership in science and technology is at risk because of a decades-long stagnation in federal support and funding for research and development. Private-sector investment has risen, but it is not a substitute for federally funded R&D directed at national economic, strategic, and social concerns.[2]

To be sure, the rising influence 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. Universities and companies are not the same. Companies must answer to investors and shareholders who expect returns on their capital investments, so they tend to focus on technologies that can be commercialized in the foreseeable future. Research universities, by contrast, operate on much longer time horizons without regard for profit, engaging in fundamental research at the frontiers of knowledge that has little if any foreseeable commercial benefit. This fundamental research is the foundation for future applications that may take years, even decades, to emerge. The "overnight success" of the COVID mRNA vaccine in 2021, for example, was the result of thirty years of university research. Similarly, it took decades of research in number theory—a branch of pure mathematics—to develop the modern cryptography that is widely used to protect data.

Today, 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 2020, two-thirds of students who received PhDs in artificial intelligence at US universities took industry jobs, leaving fewer faculty to teach the next generation (see figure F.1).[3] Only a handful of the world's largest companies have both the talent and the enormous compute power necessary for developing sophisticated large language models like GPT-4. No university comes close.

These trends have several concerning implications.[4] Among them: 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 large language models 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 F.1)—hollowing out university faculty and eroding the nation's ability to conduct broad-ranging foundational research in the field.

FIGURE F.1 Percentage of AI PhDs hired by industry



Source: Nur Ahmed, Muntasir Wahed, and Neil C. Thompson, "The Growing Influence of Industry in AI Research," *Science* 379, no. 6635 (March 2023): 884–86.

4. 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; the university lies at the heart of the innovation ecosystem. Stanford faculty, researchers, and former students have founded Alphabet, Cisco Systems, Hewlett-Packard, 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. But in this moment of rapid technological change, we must do more. We are delighted to launch this unprecedented collaboration between Stanford's Hoover Institution, the School of Engineering, and the Institute for Human-Centered Artificial Intelligence to bring policy analysis, social science, science, medicine, and engineering together.

The *Stanford Emerging Technology Review* originated from conversations we had last year with senior US government officials who came to campus and asked, "What do we need to know about emerging technologies at Stanford?" No one person had a good answer, so we convened leading scholars across fields for briefings. The impact of that day was powerful and revealing: it was a one-off event, and it was not enough. We also discovered that many of our leading faculty in different science and engineering fields did not know one another. Together we realized that although Stanford is one of the world's leading research universities, we did not know what we knew. And fragmentation was hindering our policy impact.

So we founded the Stanford Emerging Technology Review (SETR), an enduring initiative to harness the latest insights from leading scholars in ten of the most important fields today, bring these scholars together to share their research with colleagues across disciplines, and work collaboratively to enhance policy education and impact for the nation.

We selected these ten areas as a starting point, not an end point. We wanted to begin by leveraging areas of deep expertise at Stanford and covering technologies widely recognized as essential for expanding American economic prosperity, advancing democratic values, and protecting the security of the nation. But science is always moving, and we expect that future reports may focus on different areas or divide fields in different 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 to 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-Stop Shopping but Not a One-Time Product

This report is intended to be a useful "one-stop shopping" primer that covers ten key emerging technology areas: artificial intelligence, biotechnology and synthetic biology, cryptography, materials science, neuroscience, nuclear technologies, robotics, semiconductors, space technologies, and sustainable energy technologies. While this is nowhere near an exhaustive list of technology research areas at Stanford, these ten fields are rapidly shaping American society today and promise to gain importance in the coming years. Our reviews of each technology field were led by world-renowned Stanford tenured faculty members who also delivered lectures covering their fields in SETR seminars (their bios can be found in the Contributors section on page 151). The SETR team also included eighteen postdoctoral scholars and eleven undergraduate research assistants who spent the last year interviewing leading faculty across Stanford in different subfields, conducting research, and drafting background materials. Overall, they conducted seventy-five interviews spanning faculty from thirty departments on the key developments, barriers, bottlenecks, needs, opportunities, and implications in their respective fields.

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 key developments and advances in the field. Finally, each chapter concludes by offering an "over-the-horizon" outlook that covers crucial considerations for policymakers over the next few years. The report ends with two chapters that look across the ten technologies, offering analysis of common trends, key differences, and implications for economic growth, national security, environmental and energy sustainability, human health, and civil society.

Three points bear noting. **First, we offer no specific policy recommendations.** That is by design. Washington is littered with reports offering policy recommendations that were long forgotten, overtaken by events, or both. We want to provide a reference resource that endures—a report that is updated and issued annually, a guide that can inform successive generations of policymakers about evolving technological fields and their implications.

Second, *SETR* offers *a* view from Stanford, not *the* view from Stanford. There is no single view of anything in a university. Individual faculty members involved in this report may not agree with everything in it. Other members of their departments 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 those fields.

Third, this report is just the beginning. In the months ahead, SETR will be producing additional articles and reports, holding briefings in California and Washington, DC, and launching multimedia educational products. Our goal is ambitious: developing a new model to help policymakers understand tech issues in a more real-time, continuous, rigorous, and user-friendly way.

Ensuring American leadership in science and technology requires all of us—academia, industry, government—to keep listening, learning, and working together. We hope the *Stanford Emerging Technology Review* starts meaningful and lasting conversations about how an innovation ecosystem benefits us all. 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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NOTES

1. Council on Foreign Relations, *Innovation and National Security: Keeping Our Edge*, Independent Task Force Report No. 77, James Manyika and William H. McRaven, chairs, 2019, 10, https://www.cfr.org/keeping-our-edge/pdf/TFR_Innovation_Strategy.pdf.

2. Council on Foreign Relations, *Innovation and National Security*, 21.

3. Nur Ahmed, Muntasir Wahed, and Neil C. Thompson, "The Growing Influence of Industry in AI Research," *Science* 379, no. 6635 (March 2023): 884–86, https://www.science.org/doi/abs/10.1126/science.ade2420.

4. Roman Jurowetzki, Daniel Hain, Juan Mateos-Garcia, and Konstantinos Stathoulopoulos, "The Privatization of AI Research(-ers): Causes and Potential Consequences—From University-Industry Interaction to Public Research Brain-Drain?," arXiv (2021), https://arxiv.org/ftp/arxiv/papers/2102/2102.01648.pdf.