STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2025

A Report on Ten Key Technologies and Their Policy Implications

CO-CHAIRS Condoleezza Rice, John B. Taylor, Jennifer Widom, and Amy Zegart

DIRECTOR AND EDITOR IN CHIEF Herbert S. Lin | **MANAGING EDITOR** Martin Giles

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CROSSCUTTING THEMES AND COMMONALITIES

None of the individual technology areas covered in chapters 1 through 10 operates in a vacuum. It is crucial that policymakers consider broader, crosscutting themes that influence how technology progresses over time as well as the key common drivers that can accelerate or hinder progress. To give just one example, synergies between different technologies mean that a policy initiative taken in one domain may have large positive or negative impacts in other technological areas—and policymaking will improve if these potential cascade effects can be considered at the outset.

Crosscutting themes can sometimes get overlooked in the desire to take action to advance an emerging technology. By devoting an entire chapter to them, we want to underline that there are important similarities in how people and institutions make progress and that, when crafting policy for individual domains, it is essential to take a holistic view of the emerging tech landscape and the factors affecting it.

This chapter organizes these important crosscutting themes into two broad categories. The first category includes key observations about how technological development generally unfolds, including in ways that may be surprising. These observations should be regarded as important considerations in the process of formulating technology policy to promote innovation. The second category is inspired in part by the experiences of the research faculty who contributed to this report and includes major enablers of innovation. Notably, enablers come in many varieties, including technical issues, human capital, the structure and strength of innovation funding, and cognitive blind spots that can lead policymakers astray and increase the likelihood of national technological surprise.

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Key Observations About How Technologies Evolve over Time

The Goldilocks Challenge: Moving Too Quickly, Moving Too Slowly

Takeaway ***Innovation that emerges too fast threatens the legitimate interests of those who might be negatively affected, while innovation that moves too slowly increases the likelihood that a nation will lose first-mover advantages.***

Innovation typically brings two types of benefits: enhancing or improving existing processes and enabling entirely new functions that solve problems people did not even know they had.

Technological progress also brings risks. Chief among them are the risks of moving too fast or too slowly. Innovation that emerges too fast threatens to disrupt the often delicate balance that has been established among many national, organizational, and personal interests. A push to deploy new capabilities may give short shrift to issues such as safety, security, employment, values, ethics, societal impact, and geopolitics.

Examples abound. Genetically modified organisms (GMOs) have lost favor in much of Europe, largely due to safety concerns. The Concorde supersonic passenger airliner stopped flying due mostly to concerns about noise and its high operating costs. As noted in this report, concerns about the downside societal impacts of artificial intelligence (AI) are prompting calls for increased regulation of the technology. Similar concerns about the potential weaponization of synthetic biology inhibit a full-throated societal endorsement of a biotechnology-enabled future.

On the other hand, innovation that is too slow increases the likelihood that a nation will lose the technical, economic, and national security advantages that often accrue to first movers in a field. Such concerns are apparent in reports asserting that the United States is falling behind China in the development of key technologies essential for national security, such as AI.[1] Similar worries have been expressed regarding America's competition with China in technology domains considered critical to economic security.[2]

To fully realize the benefits of innovation, policy measures are often necessary to address both sets of challenges effectively.

Increasing Access to New Technologies Worldwide

Takeaway ***National monopolies on technology are increasingly difficult to maintain. Even innovations that are solely American born (an increasingly rare occurrence) are unlikely to remain in the exclusive control of American actors for long periods.***

Technologies such as synthetic biology, robotics, space exploration, and blockchain often spread from wealthy nations and large corporations to less affluent countries, smaller companies, and individual actors. Innovations that are American born are unlikely to remain in the exclusive control of American actors for long. The dissemination of many of these technologies is, in part, driven by the long-term trend of decreasing technology costs, which make these advancements accessible to a broader array of players despite efforts, such as export controls, to delay this spread.

Several key implications arise from this trend:

- Winning isn't winning anymore. The old model of achieving lasting national technological dominance is being replaced by a paradigm of continuous competition where technological advantages are not sustained for long periods.

- Greater policy complexity results from more actors. Both state and nonstate actors gain new tools to challenge US interests.

- Technological advantages are narrowing, even on the frontier. Although the United States may possess the most technologically advanced capabilities, other actors with less sophisticated versions of them can eliminate monopolies and narrow the relative advantages the United States previously had.

- There are more actors with different ethical thresholds, constraints, and perspectives. Actors with fewer bureaucratic and ethical constraints may exploit and adapt technology faster and more effectively than those with more stringent regulations.

To be sure, there are exceptions to this trend of technological diffusion. One of them is the first appearance of an emerging technology. At such a point in time, the diffusion process has not yet begun—at least not in full force—and it may indeed be that the technology in question will be characterized by the dominance of a few key actors. This is true in AI today, where a small number of private-sector actors clearly dominate the creation of large language models (LLMs). A second exception is when scale is a critical aspect of widespread innovation—actors without access to the natural resources, such as rare-earth metals, or the financial capital to support large-scale deployments are less likely to be able to take advantage of the technology.

It may be possible to extend periods of American monopoly on certain technologies, but these periods cannot be prolonged indefinitely. Extensions can help to buy time for US policymakers to better anticipate a world of technological diffusion. But all too often, buying time becomes an end unto itself, and actions to craft a better policy—such as targeted immigration reform to create a "brain gain" for American universities and companies to draw the world's best talent—are not taken.

Large and Growing Synergies Between Different Technologies

Takeaway ***The synergies between different technologies are large and growing, as advances in one technology often support advances in other technologies.***

The synergies between different technologies are both significant and expanding, as advances in one field often enhance progress in others (see sidebar on examples of synergy among emerging technologies). This point is more obvious when a field such as AI or materials science is seen as a foundational technology that impacts a variety of application domains. For example, this report has discussed how AI has facilitated innovations in battery technology and in protein folding. But what is less obvious is that AI itself has benefited greatly from advances in semiconductor technology, which has itself benefited from developments in materials science.

EXAMPLES OF SYNERGY AMONG EMERGING TECHNOLOGIES

- Artificial intelligence (AI) contributes to advances in synthetic biology by predicting the structures of various biomolecules, such as proteins, nucleic acids, and small molecules singly or joined together in various complexes.[a]
- AI helps to screen many candidate compounds to predict the ones most likely to exhibit desirable properties for materials science.[b]
- Materials science is central to the identification of new semiconductors that may be useful in developing more energy-efficient chips, which in turn can reduce the cost of training AI models.[c]
- Materials science is important in space research to create new materials for the construction of spacecraft and satellites[d] and to enable the development of neural probes that can send and receive electrical signals in neural tissue.[e]
- Energy technologies help to improve the performance of robotics and spacecraft.[f]
- Synthetic biology can build organisms that produce certain specialized materials.[g]
- Cheaper semiconductors have driven down the cost of DNA sequencing, which itself is a fundamental technology for synthetic biology.[h]

a. Josh Abramson, Jonas Adler, Jack Dunger, et al., "Accurate Structure Prediction of Biomolecular Interactions with AlphaFold 3," *Nature* 630 (May 2024): 493–500, https://doi.org/10.1038/s41586-024-07487-w.

b. This report, chapter 5 on materials science.

c. Po-Wen Chan and Balaji Chandrasekaran, "Materials Engineering: The True Hero of Energy-Efficient Chip Performance," *Applied Materials*, August 1, 2024, https://www.appliedmaterials.com/us/en/blog/blog-posts/the-true-hero-of-energy-efficient-chip-performance.html.

d. Frontiers in Space Technology, "Next Generation of Materials for Space Applications," Frontiers, accessed September 18, 2024, https://www.frontiersin.org/research-topics/55679/next-generation-of-materials-for-space-applications.

e. Yongli Qi, Seung-Kyun Kang, and Hui Fang, "Advanced Materials for Implantable Neuroelectronics," *MRS Bulletin* 48 (May 2023): 475–83, https://doi.org/10.1557/s43577-023-00540-5.

f. Anil D. Pathak, Shalakha Saha, Vikram Kishore Bharti, et al., "A Review on Battery Technology for Space Application," *Journal of Energy Storage* 61 (May 2023): 106792, https://doi.org/10.1016/j.est.2023.106792.

g. Orlando Burgos-Morales, M. Gueye, Laurie Lacombe, et al., "Synthetic Biology as Driver for the Biologization of Materials Sciences," *Materials Today Bio* 11 (May 2021): 100115, https://doi.org/10.1016/j.mtbio.2021.100115.

h. James M. Heather and Benjamin Chain, "The Sequence of Sequencers: The History of Sequencing DNA," *Genomics* 107, no. 1 (January 2016): 1–8, https://doi.org/10.1016/j.ygeno.2015.11.003.

Nonlinear Paths from Research to Useful Application

Takeaway ***The traditional linear model of R&D, in which basic research leads to applied research, which then leads to development and prototyping, which finally leads to novel and useful products or services, is only one model for how societies obtain value for investments in technology innovation.***

The traditional linear model of research and development (R&D), which progresses from basic research to applied research, leading to development and then to marketable products, represents just one way societies derive value from technological investments. This model starts with basic research focused on fundamental scientific understanding without immediate application, progresses to applied research with specific problems in mind, and moves through development to create prototypes and proofs of concept.

However, some argue that this linear approach is unrepresentative of how scientific progress actually occurs. Other models are less linear in nature, acknowledging and extolling the need for feedback between the various activities. For example, some challenging problems require a deeper fundamental scientific understanding, known as use-inspired basic research.

Research in AI on the hallucinations of LLMs fits into this category. The mechanisms that lead LLMs to generate entirely false statements known as hallucinations are not well understood today, and research continues on this topic. However, despite the fact that these errors occur frequently, LLMs continue to be useful in many walks of life.

In other cases, technology convergence can have a big impact on synergy and innovation. Here, convergence means that several key technologies each advance to the point that they are useful for a specific application, at which stage a useful innovation that draws on all of them can be produced or developed. For example, deep knowledge of drug delivery mechanisms is crucial before chemical compounds with strong anticancer properties can be turned into effective cancer treatment medications. Electric cars are another example: They were made possible by the convergence of advances in battery technology, lightweight materials, sensors, and computing power. A final example comes from chapter 6 on neuroscience in this report, which discusses how effective neurological interventions depend not only on a fundamental theoretical understanding of brain function, but also on the development of neural probes that can be implanted into the brain without causing serious damage to brain tissue.

Punctuated Technological Progress

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

Technological progress generally exhibits a variety of patterns. Progress in semiconductors has been fairly predictable historically, progressing consistently with Moore's law, which predicts a steady exponential decrease in cost over time. But, as noted in chapter 8 on semiconductors, this steady decline is coming to an end, if it hasn't expired already. Solar cells and light-emitting diode (LED) lighting have followed similar cost reduction curves, except that these cost decreases are usually represented as a function of manufacturing experience and expertise rather than time.[3]

But most other technologies have demonstrated much more uneven progress, characterized by extended phases of gradual development interrupted by sudden, transformative bursts of innovation. Sometimes, these bursts result from particular breakthroughs, such as the personal computer revolution of the 1980s and the emergence of the World

Wide Web in the early 1990s. Other times, they are due to the simultaneous availability and maturity of several key technologies that are required to make significant progress in some other technological domain—the convergence phenomenon mentioned earlier in this chapter.

Predicting future progress can be challenging and misleading due to the pattern of punctuated innovation. Even experts in a given field can be surprised by the rapidity of progress. For instance, Geoffrey Hinton, one of the pioneers in AI and a winner of the 2024 Nobel Prize in Physics for his application of tools and concepts from statistical mechanics to machine learning, recently expressed astonishment at the swift progress in AI and predicted that it will surpass human intelligence in the future. At the same time, chapter 1 on artificial intelligence notes that the transformative impact of AI on the US military has been slower than is required to ensure that the United States will retain the technological advantages it currently has over adversary forces.

Another example is nuclear fusion for sustainable energy. The previous edition of the *Stanford Emerging Technology Review* (*SETR*) described breakthroughs in nuclear fusion—two better-than-breakeven experiments conducted at the Lawrence Livermore National Laboratory. A flurry of excitement at the time—quite justified on scientific grounds—led to many overly optimistic news stories about inexhaustible supplies of energy whose tone conveyed a sense of rapid change in the field.[4] Since then, two more experiments have been performed, demonstrating repeatability. While repeatability is in itself an important scientific milestone, fusion is a long way from technical viability as a sustainable energy source, and most experts believe that prospects for commercialization remain decades away.

The punctuated nature of technological change suggests that expectations of regular and rapid change in most fields are generally not realized, despite what headlines in the news might lead one to believe.

Nontechnological Influences on Technological Innovation

Takeaway ***Technology applications in society require scientific proof of concept, engineering feasibility, economic viability, and societal acceptability.***

Scientific advancements are frequently highlighted in the news for their promise to address societal challenges and enhance our quality of life. However, there is often a large gap between a demonstration of scientific feasibility and the creation of a product or service based on the technology that is useful to society.

To be sure, scientific feasibility is a necessary prerequisite, but it may well be that other necessary forms of feasibility do not follow. First, after achieving scientific proof of concept, a given technology application must demonstrate engineering practicality. An example is the idea of a single-stage-to-orbit, chemically fueled spacecraft launched from Earth. With current rocket fuels and materials, it is generally believed that it is possible—though barely—to launch a spacecraft using a single rocket stage rather than multiple stages. What has not yet been demonstrated is a feasible engineering design that would reliably accomplish this task.

Economic viability and practicality come after engineering feasibility, and these involve considerations such as cost and ease of use. Early attempts to build supercomputers with superconducting components demonstrated technical success but faced practical challenges due to the need for liquid helium for cooling. This requirement made the computers difficult and costly to deploy, and the development of alternative technologies offering comparable performance at lower cost doomed the approach in the marketplace.

Next, there is the cost of manufacturing. It may prove too difficult to develop a manufacturing process to build a product or service based on the initial scientific proof of concept, or the materials used to demonstrate engineering feasibility may turn out to be too expensive or rare to support large-scale production. Cheaper alternatives may also become available, undermining the commercial viability of the original concept.

An illustration of this phenomenon can be found in the competition between lithium-ion (Li-ion) and sodium-ion batteries. Sodium-ion batteries have potential cost advantages over Li-ion ones because sodium is much more abundant than lithium. But Li-ion battery technology has a head start of a couple of decades that has driven down the cost of these batteries significantly. Thus, the economics of procurement today favor Li-ion in many of the most common applications—although any significant disruption of the lithium supply chain could make sodium-ion batteries more broadly competitive.

Societal acceptability matters as well. The psychology of individuals, as well as cultural practices and beliefs of a community or society, contribute to the adoption and use of any given technology application. For instance, in Europe, GMOs as food are highly controversial, and concerns over their safety have prevented the uptake of GMO foods that are consumed widely in the United States.

Finally, the road from scientific discovery to useful application is often rockier than expected, with would-be innovators finding that the realization of the benefits promised to investors and customers actually entails greater costs than planned, takes longer than anticipated, and delivers fewer capabilities than expected. They may stumble for other reasons, too, ranging from difficulty finding sufficient funding to advance innovations and challenges over environmental or other impacts. Moreover, risks associated with things such as ethics and equity, privacy, and increased challenges to health, safety, and security—all issues that could lead to an erosion of trust in a product or service—may become apparent only once it is being sold to customers.

The Changing Role of Government in Technological Innovation

Takeaway ***The US government is no longer the primary driver of technological innovation or funder of R&D.***

Plenty of technological innovations, including satellites, jet engines, and semiconductors, have their roots in US government financial support and advocacy. But in many fields today, the government is no longer the primary driver of innovation. Private companies have taken up much of the slack. These companies, however, may be under the jurisdiction of nations—or controlled by senior executives—whose interests are not aligned with those of the users of their services. The Starlink satellite communications network has been an essential part of Ukrainian battlefield communications; however, the CEO of Starlink curtailed Ukrainian access on a number of occasions in ways that affected Ukraine's battlefield strategy.[5] Such concerns are most serious when there is only one or just a small number of private-sector providers of the services in question.

The growing influence of private companies in critical technologies has led US officials to emphasize the need for closer public-private cooperation and government regulation. Even if the government cannot lead in innovation, it still plays a crucial role in funding R&D, promoting key innovations, setting standards, and forming coalitions domestically and internationally.

No better example of the growing influence of private companies in setting the R&D agenda can be found than in the current scene for the funding of AI research today. Whereas the federal government talks in terms of billions of dollars in federal support for AI research, the private sector is talking in terms of amounts ten to a hundred times larger. Similar trends seem to apply to biotechnology and synthetic biology research, though not quite as starkly. And, as chapter 9 on space discusses, services related to space are increasingly delivered by private companies.

It's also true that national priorities change with the evolution of the geopolitical environment. In the 1990s, there was widespread optimism about the triumph of liberal democracy and free market capitalism. Much of US economic policy was characterized by efforts to support free trade, accelerate globalization, and promote China's integration into the world economy as a way of facilitating its transition to more democratic rule.

During this time, the global manufacturing landscape for key technologies, particularly semiconductors, underwent significant shifts. Over three decades, the US share of global semiconductor production dropped from 37 percent to 12 percent, as noted in chapter 8 on semiconductors. Meanwhile, Asian manufacturers, especially in South Korea and Taiwan, emerged as major players, supported by government policies and regional demand shifts. Asia had become the dominant region for semiconductor production, laying the groundwork for the current global supply chain.

This shift in manufacturing capabilities, coupled with China's economic and military rise, is a key element of changes in the geopolitical environment and drives many Western concerns about technological dependencies in the twenty-first century. Accordingly, national policies that were seen as useful and appropriate in the environment of thirty years ago may need reassessment today.

The story of advanced chip fabrication is instructive. The most advanced chips made today require a laser technology called extreme ultraviolet (EUV) lithography, which uses tiny explosions of molten tin made at extreme speeds and bounced off the flattest mirrored surfaces in the world to produce an extremely short wavelength of light. Shortening light wavelengths is the key to shrinking the size and increasing the density of transistors on a chip, making it faster and more powerful.

Major breakthroughs in this laser technology were developed by researchers at Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory, and Sandia National Laboratory in the 1990s, and intellectual property rights were owned by the US government but licensed under approval by Congress and the Department of Energy (DOE). The Dutch company ASML applied for a license, and at the time no objections were raised.

Today, ASML is the only company in the world that can manufacture and service the sophisticated machines using EUV technology, each of which costs about $200 million.[6] The future development of advanced semiconductor manufacturing equipment to shrink transistor dimensions even more—as well as balancing market access with the national security concerns of exporting to and servicing ASML equipment in China—are major geopolitical and economic concerns.[7]

The Relationship of Political Regime Type to Technological Progress

Takeaway ***Democracies provide greater freedom for scientific exploration, while authoritarian regimes can direct sustained funding and focus on technologies they believe are most important.***

Technological innovation occurs in both democracies and autocracies, but different regime types face different advantages and challenges. Democracies benefit from the rule of law, a free flow of ideas and people, and the freedom for individuals to pursue their own research interests. Perhaps most importantly, because failure in a democracy does not lead to persecution or necessarily result in professional ostracism, individuals are freer to experiment and explore. By contrast, authoritarian regimes are characterized by the rule of the state and dire consequences for failure, which can restrict the flow of ideas, force adherence to state-approved research areas, and prompt scientists to focus only on what are considered safe topics.

On the other hand, authoritarian regimes can direct sustained funding and attention to areas deemed crucial by the state more easily than democracies and maintain focus on these areas for extended periods, independent of short-term profit or political considerations. For example, it is widely accepted that Chinese AI efforts have access to the personal data of individuals on a far broader scale than those in the West, which generally has stronger privacy protections against government intrusion than China does.

In the United States, recent attempts to adopt more centralized technology-policy approaches—such as the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act of 2022 supporting the semiconductor sector—aim to capture some benefits associated with authoritarian direction while preserving democratic values. Critics argue that such measures interfere with free markets and create inefficiencies by selecting winners and losers. Conversely, advocates believe these policies are necessary to counterbalance the advantages of authoritarian regimes. The challenge is to find a balance that aligns with American values while enhancing economic competitiveness.

Common Innovation Enablers and Inhibitors

The Central Importance of Ideas and Human Talent in Science and Technology

Takeaway ***Human talent plays a central role in generating the ideas for innovation; such talent can be found all over the world and cannot be manufactured at will.***

Scientific progress thrives on new ideas, which are generated daily by the most talented individuals worldwide. But human talent capable of creating ideas in science and technology cannot be generated on demand. Such talent must be acquired from foreign sources and/or nurtured domestically.

Foreign sources of talent make critical contributions to US science, technology, engineering, and mathematics (STEM). Although America remains the single most prominent contributor to global R&D, other nations—most notably China—are rapidly increasing their investments in this area. Geographic concentration of R&D expenditure continues its shift from the United States and Europe to East, Southeast, and South Asia.

This trend highlights the increasing importance of international collaboration. US researchers undoubtedly benefit from ideas developed abroad by reading scientific literature from other countries, but direct interactions with foreign researchers are often more valuable because they provide more comprehensive and expansive insights. Such interactions help American researchers acquire tacit knowledge that is not captured in published papers, including research directions that appeared promising but did not ultimately bear fruit. These interactions also offer a deeper understanding of foreign scientific progress. This point about the importance of tacit knowledge in scientific advancement has been made by many scholars[8] and was strongly expressed in a multitude of interviews with Stanford faculty working in the technology areas addressed in this report.

America's ability to attract and retain foreign talent is essential for maintaining its innovation edge, and domestic innovation is hindered when limitations are imposed on interactions with foreign scientists and their research. Skilled immigrants play a crucial role in American innovation, with immigrant college graduates receiving patents at twice the rate of native-born Americans.[9] More generally, a broader pool of people will yield higher quality talent than digging more deeply into an existing pool of people simply because the broader pool is more likely to have a greater number of individuals at the high end of the talent distribution.

However, US policies that discourage immigration can reduce the influx of skilled workers, impacting the country's capacity for innovation.[10] They also shift skilled talent and multinational R&D investment to other countries, including both strategic competitors such as China and close allies such as Canada.[11] Such a shift can also force US companies to relocate abroad due to worker shortages.[12] Finally, many academic researchers are immigrants on student visas. Without a clear route to permanent residence, the United States could lose key teaching and research talent in vital STEM domains.

Immigration policies affecting the labor force can make it harder to meet goals in industries like semiconductors, biotechnology, and sustainable energy. US workers still make up the majority of the US STEM workforce, although foreign-born talent accounts for an increasingly large fraction of it. Even if the trend toward greater foreign participation in STEM jobs continues—and especially if it were to reverse—strengthening the domestic pipeline of STEM workers is essential for several reasons.

First, a number of studies indicate a strong correlation between a nation's STEM education and economic growth and productivity.[13] Correlation is not causation, but the connection is unlikely to be accidental or spurious.

Second, other nations—including nations such as China and India that are presently important providers of US STEM talent—are investing more heavily in scientific R&D. Individuals who have previously chosen to work and study in the United States may well take advantage of opportunities at home in greater numbers. Foreign-born individuals working in the US STEM workforce may have family or personal ties in their nations of origin that tempt them to return. Those nations may also take steps that explicitly discourage their scientists and engineers from studying or working in the United States.

Third, a STEM worker educated in the United States is more likely to have personal and citizenship loyalties to the United States and can fairly be regarded as more likely to remain in the country.

Fourth, many security-sensitive jobs require US citizenship. In 2021, the US Department of Defense (DOD) noted that improving the capacity and resilience of the defense industrial base requires more workers trained in STEM,[14] also observing that the dearth of trained software engineers working on classified projects was in part because of the requirement that they must be US citizens.

In promoting a more robust domestic contribution to building STEM expertise in America, it is sobering to realize that the United States is facing a decades-long decline in K–12 (kindergarten to twelfth grade) STEM proficiency,[15] with standardized testing revealing declining scores in fourth- and eighth-grade mathematics.[16] While COVID-19 disruptions account for some decline,[17] the 2023 scores follow a twenty-year trend of diminishing STEM proficiency.[18] In 2022, American thirteen-year-olds had the lowest math and reading scores in decades, with math literacy declining across all demographics and regions.[19] A 2023 American College Testing (ACT) report found that 70 percent of high school seniors failed to meet college readiness benchmarks in math,[20] highlighting a critical challenge for the nation's economic and technological competitiveness.

Of particular concern is that at the top end, only 7 percent of American teens scored in the highest level of math proficiency as measured by the Program for International Student Assessment, a test to assess student ability to apply knowledge in real-world situations administered by the Organisation for Economic Co-operation and Development. This compares to 12 percent of Canadians and 41 percent of Singaporean teens scoring in the same top category.[21]

Adding to the challenge is a growing shortage of qualified STEM educators in the United States—about 28 percent of grade-seven to grade-twelve science teachers do not have a degree in the sciences, and about 40 percent of math teachers in high-poverty-area schools do not have a math degree.[22] Teachers in low-performing schools and in schools with higher concentrations of minority students are more likely to have less experience and report feeling underprepared for STEM instruction.[23]

Today, both paths to growing the requisite talent base to sustain and grow US innovation face serious and rising challenges. The global competition for talent means that the United States must adopt a more strategic approach to leveraging international expertise, as connections between American science and technology efforts and those of the rest of the world will accelerate the nation's progress in critical technology fields. To maintain and enhance its innovation capacity, the United States urgently needs to improve its own STEM education across all demographic groups, provide better pathways for skilled immigrants to remain in the United States, and invest more in human capital.

Concerns about foreign appropriation of American intellectual efforts are not without foundation. But using a meat axe to make widespread and blunt cuts in opportunities to collaborate with foreign scientists when a surgical scalpel is needed to curb only the issues that warrant serious concern is a sure way to undermine the effectiveness of US scientific endeavors.

Frontier Bias in Policymaking

Takeaway ***A policy bias toward science or technology at the frontiers of knowledge tends to overestimate the benefits accruing from such advances, at least in the short term. Many technologies with transformational potential are not necessarily on the technical frontier.***

A frontier bias is a tendency among analysts, commentators, and policymakers to focus on the significance of the newest and most recent innovations. Such a trend has been apparent even in the uptake of the inaugural *SETR* report—requests for briefings arising from its publication have most often focused on what's newest and most advanced in various fields.

But a frontier bias, while understandable, carries with it the risk of overlooking "old" technologies that can be used in novel and impactful ways. Innovation using proven and known technologies is a powerful way of advancing national and societal interests and by definition does not rely on scientific or technological breakthroughs.

One prominent example is technology being used in the present Russia-Ukraine war. For instance, the drones having the most effect on the battlefield area are a diverse mix of moderately sophisticated ones and off-the-shelf commercial drones. And in response to US trade sanctions on advanced semiconductors, Russia is making use of chips designed for home and commercial use to control its weapons.

Another example is the widespread use of the AK-47 automatic rifle. Unlike other popular guns, the AK-47 was deliberately designed to be low-tech—cheap, simple, and durable, as well as easy to manufacture and with few moving parts. It has since proliferated: Some seventy-five million of these guns are in operation today, and they have had an enormous impact on forces around the world,[24] most notably insurgent groups and terrorists.[25]

The story in chapter 10, on sustainable energy technologies, about a second life for electric vehicle (EV) batteries is also relevant here. As EVs become more widely used, the batteries powering them—still with significant capacity for power storage—will constitute a waste stream if other uses cannot be found for them. With specialized battery management systems tailored to their unique characteristics, these batteries can serve in stationary energy storage applications, such as acting as backup power sources for the grid. Their age will mean the batteries may not be at the cutting edge of battery technology when they are converted, but they will have significant capacity that would otherwise be thrown away.

A frontier bias, while understandable, carries with it the risk of overlooking "old" technologies that can be used in novel and impactful ways.

A second consequence of frontier bias is a misunderstanding of the difference between scientific or technological advances and adoption at scale. For example, in the couple of decades after the first generation of commercial nuclear power in October 1956, there was considerable optimism that further technological advancements in the field would bring about an era in which electrical energy was too cheap to meter. But as discussed in chapter 10, nuclear fission has not been widely adopted as a source of energy for a variety of technical, economic, and political reasons.

For an innovation to have significant societal impact, it needs to be broadly available and widely used. At one extreme, some innovations can be acquired on a small scale by individuals. The rapid spread of personal computers in the 1980s and of rooftop solar panels for home electricity generation are examples—people were willing to spend money out of their own pockets to derive the benefits of these innovations and the result was rapid uptake and adoption throughout society.

By contrast, advanced technology that requires a significant degree of centralized planning and/or funding for realization is likely to be adopted on much longer timescales. Nuclear energy requires the construction of nuclear reactors costing billions of dollars. State-of-the-art semiconductor plants come at the cost of tens of billions. Medicines for treating neurodegeneration are available only at the end of a very expensive drug approval and manufacturing process. Carbon capture and sequestration is too expensive to be widely adopted and is of marginal benefit for individuals, though it is of use to industrial facilities. For such innovations, it is unrealistic to expect rapid and widespread adoption throughout society.

Optimism, Pessimism, and Realism in Technology Policy

Takeaway ***Good public policy anticipates wide variations in perspectives on any given technology.***

This publication focuses on ten emerging technologies of significance. In putting together the latest edition of *SETR*, every faculty member interviewed from each of these technology areas was broadly optimistic about the societal and scientific value of work that is being conducted in their chosen domains.

This is hardly a surprise. If they were not optimistic about the value of work in those fields, why would they continue to work in them? Technological optimism—a belief that technological advances will continue to accrue and that such advances will solve important problems—is virtually a requirement for people to spend large parts of their lives working to invent or invest in a new technology.

But an optimistic view of technology cannot and should not be the only voice shaping technology policy. When everyone in a decision-making organization shares similar perspectives on technology—creating analytical blind spots and, potentially, groupthink (unwarranted conformity in beliefs)—the risks associated with innovation can be underestimated. It is therefore important to have voices in the decision-making process that anticipate and articulate potential downsides of a given technology. The people with these voices play a critical role in identifying possible negative consequences of new technologies—such as privacy concerns, ethical dilemmas, or societal disruptions—and in devising ways to mitigate those risks before technological lock-in makes it difficult or impossible to address their root causes. A set of individuals with different knowledge and backgrounds who are involved in the decision-making process will generate a more comprehensive understanding of potential risks and benefits and avoid damaging groupthink.

The optimists and advocates of a particular technology will almost always dismiss early attention to potential downside risks as being premature and likely to stifle or retard innovation. But such downsides will almost always exist when a new technology is adopted at a large scale. By actively searching for voices that can explain the potential downsides early in a technology's life cycle, policymakers can create a more balanced and forward-thinking policy environment that reduces risks while fostering innovation.

Another important issue when it comes to developing a framework for shaping policy is the double-edged nature of leapfrog developments in technology. For individual businesses, such breakout events can offer competitive advantages and open new markets. However, for nations, these rapid changes can pose strategic challenges when the scale of adoption reaches a sufficiently high level. At that point, countries that did not anticipate and/or prepare sufficiently may find themselves vulnerable to strategic surprises that could impact national security, economic stability, or social cohesion.

Finally, there needs to be a recognition that the process of creating effective technology policy can be slow and complex due to the need to mesh various perspectives together. Only by engaging in thorough deliberation and incorporating diverse viewpoints can policymakers shape an environment that is both well suited to the speed of technological progress and able to adapt to the inevitable uncertainties that accompany it. This approach ensures that public policy remains adaptable and capable of addressing both the ups and downs of technological advancements.

Universities and Technology Innovation

Takeaway ***US universities play a pivotal role in the innovation ecosystem that is increasingly at risk.***

The US R&D infrastructure is extensive, with significant contributions from both the private sector and federal government. Historically, private-sector research entities such as the former Bell Laboratories, IBM's Thomas J. Watson Research Center, and Xerox PARC have performed a substantial amount of foundational scientific research. However, such organizations now focus primarily on applied research tied to their commercial interests. This shift means that their research often targets immediate, practical applications rather than long-term, fundamental breakthroughs. Moreover, corporate R&D outputs tend to be proprietary, limiting their accessibility and broader impact.

The federal government also operates a large number of laboratories and Federally Funded Research and Development Centers (FFRDCs), including those run by the DOE, the DOD, and NASA. These mission-driven laboratories aim to address particularly difficult problems that go beyond the capacity of private industry or individual universities.

Universities play two unique and pivotal roles within the innovation ecosystem that are often underappreciated. First, they have the mission of pursuing high-risk research that may not pay off in commercial or societal applications for a long time, if ever.[26] (The sidebar on the long-term reach of university research offers some examples.) Unlike mission-driven federal labs, universities have a broader scope and breadth of research, and unlike the private sector, they conduct open, transparent research that promotes accountability, collaboration, and broad impact. This openness accelerates discovery by making study details, data, and results accessible to others. One significant data point is that more than 80 percent of the algorithms used today—not just in AI but in all kinds of information technology—originated from sources other than industrial research.[27] University openness magnifies educational and societal benefits by enabling other researchers to build on prior work, thus driving innovation forward.

THE LONG-TERM REACH OF UNIVERSITY RESEARCH

Research in number theory—a branch of pure mathematics—was undertaken for decades before it became foundational to modern cryptography.

In the 1960s, academic research on perceptrons sought to develop a computational basis for understanding the activity of the human brain. Although this line of research was abandoned after a decade or so, it ultimately gave rise to the work in AI on deep learning several decades later.

The term *mRNA vaccines* entered the public lexicon in 2021 when COVID-19 vaccines were released. Yet development of these vaccines was built on university research with a thirty-year history.[a]

Magnetic resonance imaging (MRI) was first discovered in university studies in the 1940s, but it took another three decades of research, much of it university based, for the first medical MRI imagers to emerge.

a. Elie Dolgin, "The Tangled History of mRNA Vaccines," *Nature*, October 22, 2021, https://www.nature.com/articles/d41586-021-02483-w.

Second, as educational institutions, universities play the central role in producing meaningful STEM expertise in the next generation. Any long-term plan for STEM leadership globally has to take into account how to sustain any advantages that the United States has—and US higher education in STEM is still the best in the world. This leadership is reinforced by the strength of America's university-based research enterprise: There is no better way to learn how to do state-of-the-art research in STEM than to actively participate in such work. By providing students with hands-on research experiences, access to cutting-edge facilities, and mentorship from leading experts, US universities create an environment where the next generation of STEM leaders can flourish.

Throughout history, government-supported university research has played a key role in technological advancements, from radar and proximity fuses during World War II to modern developments like AI and mRNA vaccines. It has generated knowledge whose exploitation creates new industries and jobs, spurs economic growth, and supports a high standard of living while also achieving national goals for defense, health, and energy.[28] It has also been a rich source of new ideas, particularly for the longer term, and universities are the primary source of graduates with advanced science and technology skills.

University research and development funding from all sources has grown significantly, reaching nearly $90 billion in 2021.[29] While private-sector investment in technology and university research has increased, it cannot replace federal funding, which supports R&D focused on national and public issues rather than commercial viability.[30] The US government remains uniquely capable of making large investments year after year in basic science at universities and national laboratories, which is essential for future applications. However, its share of academic R&D funding has declined over the past decade, standing at 55 percent of total support for academic R&D in 2021, the most recent year with available data.

As measured against GDP, funding trends are also negative. The fraction of GDP that goes to R&D could fairly be regarded as a seed corn investment in the future, yet federal R&D funding has gone from 1.86 percent of GDP in 1964 to just 0.66 percent of GDP in 2016.[31]

A constrained budget environment largely accounts for these negative funding trends. For example, the CHIPS and Science Act of 2022 authorized dramatically increased funding for basic research—about $53 billion—but Congress provided only $39 billion.[32] The United States still funds more basic research than China, but Chinese investment is rising much more rapidly and will likely overtake that of the United States within a decade.[33]

Moreover, despite their vital contributions, universities face challenges due to the blurring line between fundamental and export-controlled research, which complicates international collaboration in fields such as semiconductors, nanotechnology, AI, and neuroscience. For example, some researchers worry that fundamental research, which should be a less sensitive area, could now be considered export controlled and may shy away from foreign collaboration out of an abundance of caution. While well intended, these kinds of expanding restrictions may backfire in the long term, holding back US progress in key technological domains. Restrictions are not the only challenge; policy ambiguity is also harmful because it can discourage or deter collaboration with non-US researchers wishing to contribute to work in the United States.

All of these policy issues, widely recognized among the research community and apparent in interviews with Stanford faculty for this publication, underscore the urgent need for clarification and reform to advance research and promote effective international collaborations.

The Structure of Research and Development Funding

Takeaway ***Sustaining American innovation requires long-term government R&D investments with clear strategies and sustained priorities and not the wild swings from year to year that have become increasingly common.***

Budget is an obvious aspect of government funding for R&D, but three other aspects deserve at least as much attention. First, the government plays an important role in funding long-term precompetitive research that industry is not structured to support. Second, frequent shifts in funding levels, which are becoming increasingly common in government funding, undermine systematic R&D efforts and drive away scientific talent that opts to find employment elsewhere. Third, the so-called valley of death, a period occurring after demonstrating the engineering feasibility of an innovation but before it achieves large-scale adoption and commercial viability, is a significant problem.

When a new innovation is first offered to customers, its cost relative to what it is capable of can impact its success. High initial costs can deter the public from purchasing or using the innovation, potentially leading to a firm's commercial failure in the absence of external funding. However, as production volume increases, per-unit costs typically decrease due to the learning curve in manufacturing. This cost reduction is critical, especially in sectors like energy production where large-scale deployment offers significant societal benefits.

The problem is that researchers and young companies trying to get to this point must first find ways to scale their activities, and raising money to do this can be challenging. Research funding typically ceases once the feasibility of a technology has been demonstrated. If no alternative sources of money are found—or those that are available are not sufficient to get projects to critical scale—then those projects may have to stop or progress much more slowly. In some cases, innovations never scale beyond the initial stages, regardless of their technical sophistication or desirability.

For a firm to get through this valley of death, it must either secure investors who believe in the innovation's potential or attract enough customers to sustain operations. True commercial viability typically requires reducing per-unit costs to an affordable level for most customers. This can be particularly challenging for projects that require very large capital investments.

Bridge funding, which could come from government entities, banks, or other sources, may help to establish commercial viability, but an ongoing challenge is distinguishing between genuinely promising innovations and those that merely appear to be innovative but are not commercially viable. Firms failing to cross the valley of death could be acquired by foreign competitors—in particular, China—that have a greater willingness to invest in a technology that has not yet proven itself in the marketplace.

Focused research organizations (FROs) are a new funding model designed to bridge the valley of death by providing financial support to teams of scientists and engineers for rapid prototyping and testing. Convergent Research, a nonprofit established in 2021 to support FROs, received $50 million in philanthropic donations in March 2023 to start two new FROs.[34]

Cybersecurity

Takeaway ***Researchers working in highly competitive environments who neglect cybersecurity place their research progress at risk.***

Cybersecurity refers to technologies, processes, and policies that help to protect computer systems, networks, and the information contained therein from malicious activities undertaken by adversaries or unscrupulous competitors. Traditionally, cybersecurity has focused on protecting computer systems from unauthorized access and misuse, emphasizing the core principles of data confidentiality, integrity, and availability. Confidentiality ensures data privacy, preventing unauthorized disclosure. Integrity maintains data and program accuracy, guarding against unauthorized alterations. Availability ensures data and computing resources are accessible to authorized users, especially during critical times.

Initially, cybersecurity as a technical discipline focused on secure programming languages and robust software architectures, which created systems more resistant to threats like malware and advanced cyberattacks. The internet's growth and the proliferation of networked devices required security that also encompassed protecting the infrastructure that supports data transmission and storage.

Cybersecurity has continued to evolve, focusing on challenges from social engineering attacks and digital misinformation, recognizing that human interaction with computer systems is a threat vector. It has also focused on the risks of increasing information warfare and cyber-enabled information operations.[35] Further research addresses threats posed by the emergence of AI at both human and system levels.

As a national-level issue, cybersecurity policy measures are often associated with private-sector businesses and government. But cybersecurity is also a critical concern for R&D in academia and industry.

One major cybersecurity interest is ensuring the integrity of data. Data generated from scientific experiments are fundamental to research progress, and the deletion or destruction of data can severely hinder scientific advancement. More insidiously, if data are subtly altered, this can skew results in ways that are difficult to detect, potentially leading researchers down the wrong path and wasting valuable effort. Computer programs are also susceptible to such risks, as minor changes can go unnoticed for long periods of time and call into question the validity of previously collected or analyzed data.

A second interest in cybersecurity is protecting the confidentiality of work products, such as datasets and working papers. Unauthorized access to confidential datasets can breach agreements and compromise academic integrity, while premature disclosure of draft working papers can undermine claims of priority and reveal incomplete, inconsistent, or inaccurate information.

Computers managing data collection from laboratory instruments are also vulnerable to attacks that could disrupt data collection, corrupt data, and damage equipment. Such attacks can have severe repercussions for research continuity.

Technical safeguards exist to address these cybersecurity challenges, but maintaining them in academic settings requires substantial management effort. This effort can clash with the informal, collegial, and flexible cultures common in labs, where rigorous security practices may be perceived as disruptive.

Cybersecurity issues also arise with the development and use of the foundational models of AI. These models are generally trained on enormous amounts of data. A malicious actor could attack a large language model (LLM) trained on textual data by posting corrupted data online that is subsequently used to train the model. Publicly accessible LLMs can also be attacked by users seeking to circumvent the models' safety guidelines to obtain outputs that they would otherwise not disclose, such as how to make a deadly poison.

Another cybersecurity threat involves the selective targeting of personnel involved in key research projects. It is quite possible that these individuals may be harassed via cyberspace. This activity may include compromising personal finances or threatening researchers' families, which can be distressing for both the scientists and their family members. Another tactic involves questioning an investigator's professional ethics on social media and in other online forums, which can damage their reputation and productivity.

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STANFORD EXPERT CONTRIBUTOR

Dr. Herbert S. Lin

SETR Director and Editor in Chief, Hank J. Holland Fellow in Cyber Policy and Security at the Hoover Institution