STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2026

A Report on Ten Key Technologies and Their Policy Implications

CO-CHAIRS Condoleezza Rice, Jennifer Widom, and Amy Zegart

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

11

CROSSCUTTING THEMES AND COMMONALITIES

None of the individual technology areas covered in chapters 1 through 10 operate 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. By devoting an entire chapter to them, we wish to underline the important similarities in how people and institutions make progress and emphasize 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 crosscutting themes into four categories:

- **Governance and Geopolitics of Emerging Technology** examines how governments and political systems shape global technological progress.
- **Innovation Pathways and Patterns of Progress** explores the diverse ways in which technological progress unfolds.
- **Human Capital and Knowledge Ecosystems** highlights the critical roles of people, universities, and funding structures in driving and sustaining innovation.
- **Infrastructure for Innovation** encompasses vital systems and structures that support innovation on a large scale.

Governance and Geopolitics of Emerging Technology

KEY TAKEAWAYS

- 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.
- 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.
- The US government is no longer the primary driver of technological innovation or funder of research and development (R&D).
- While democracies provide greater freedom for scientific exploration, authoritarian regimes can direct sustained funding towards—and maintain focus on—technologies they believe are most important.

The Goldilocks Challenge: Moving Too Quickly, Moving Too Slowly

Technological progress creates risks related to speed. Moving too quickly can disrupt understandings, written or unwritten, that balance a variety of legitimate national, organizational, and personal interests. Rapid or accelerating change could also have a negative impact on safety, security, employment, ethical considerations, societal impacts, and geopolitics. The result could be a public backlash against a particular technology. For example, genetically modified organisms (GMOs) have faced public resistance in Europe due to safety concerns, the Concorde supersonic aircraft was retired over noise and cost issues, and calls for artificial intelligence (AI) regulation reflect fears of the technology's societal impact.

Conversely, 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 considered critical to both national security and economic security, such as AI.[1]

To fully realize the benefits of innovation, policy measures must address both the risks of rapid change and the dangers of falling behind.

Increasing Access to New Technologies Worldwide

A fundamental reality of today's technological environment is that American-born innovations are unlikely to remain in the exclusive control of American actors for long. The diffusion of many of these technologies is, in part, driven by the long-term trend of decreasing information technology costs, but other factors play important roles as well.

Access to and use of these technologies has spread beyond US borders because of global business models that have increased the potential customer base by leaps and bounds.[2] Digital platforms and strong network effects have driven rapid, global user adoption.[3] Open-source initiatives and collaborative research have accelerated diffusion of the underlying technologies by lowering entry barriers and encouraging adaptation across borders.[4] Offshore manufacturing of American-designed innovations and licensing of these innovations has brought technical know-how within the reach of potential overseas competitors.[5] Foreign competitors steal US intellectual property worth hundreds of billions of dollars per year.[6] Technological knowledge is often reverse-engineered or reimagined internationally.[7]

Several key implications arise from increasing access to new technologies:

- 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 rarely, if ever, sustained for long periods.

- More state and nonstate actors are obtaining access to advanced technologies, gaining new tools to challenge US interests. This makes formulating policies even more complex.

- Technological advantages are narrowing, even on the frontier. Although the United States may possess the most technologically advanced capabilities in certain domains, other actors with less sophisticated—but still effective—versions of advanced technologies can reduce first-mover advantages the US previously enjoyed.

- There are more actors with different ethical thresholds, constraints, and perspectives. Those 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 faster and wider technological diffusion. Perhaps the most important of them are instances when scale is a critical aspect of widespread innovation and those in which actors lack access to the natural resources (such as rare-earth metals) or financial capital needed to support large-scale deployments. This has been true for much of the past with respect to nuclear weapons, where the major roadblock for nations seeking to acquire such weapons has been getting access to fissile materials rather than to necessary knowledge. It is also true in AI today, where a small number of private-sector actors clearly dominate the creation of large language models (LLMs).

It may be possible to extend periods of American monopoly on certain technologies (e.g., through the application of export controls to key components of them), but these periods cannot be prolonged indefinitely. Extensions can help to buy time for US policymakers to better anticipate the consequences of a technology's diffusion in the future. But all too often, buying time becomes an end unto itself, and actions to craft a better policy that could help sustain US leadership in key domains—such as targeted immigration reform to attract more of the world's best talent and create a "brain gain" for American universities and companies—are not taken.

The Changing Role of Government in Technological Innovation

Many technological innovations, including satellites, jet engines, and semiconductors, have their roots in US government financial support and advocacy. But in many fields today, the US government is no longer the primary driver of innovation. Private companies have taken up much of the slack. These businesses, 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. For example, the Starlink satellite communications network has been an essential part of Ukrainian battlefield communications; however, the CEO of Starlink has curtailed Ukrainian access on a number of occasions in ways that affected Ukraine's battlefield strategy.[8] Such concerns are most serious when there is only one—or just a small number—of private-sector providers of the services in question.

No better example of private companies' growing influence in setting the R&D agenda can be found than in the current scene for funding AI research. Whereas the federal government talks in terms of billions of dollars in federal support for AI research, the private sector talks in terms of amounts a hundred or more times larger. Similar trends seem to apply to biotechnology and synthetic biology research, though not quite as starkly. And, as chapter 10, on space, discusses, services related to space are increasingly being delivered by private companies.

EXTREME ULTRAVIOLET AND ADVANCED CHIP FABRICATION

Advanced chip fabrication is a domain of national technology policy in which developments appropriate thirty years ago may need reassessment today. The most advanced chips currently being made require light in the extreme ultraviolet (EUV) range (13.5 nanometers). The method used today for producing EUV light uses high-energy laser pulses to vaporize tiny droplets of tin to create a plasma that emits EUV light. This light is then precisely reflected and focused by some of the flattest mirrors in the world to etch the intricate patterns needed for advanced semiconductor chips. This technology is key to increasing circuit density on advanced chips, making them 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 US Department of Energy. 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. Regular EUV machines cost about $200 million each, but the newer high-numerical-aperture EUV systems cost closer to $370 million, and ASML can manufacture only a handful annually.[a] The future development of advanced semiconductor manufacturing equipment that will increase circuit density on chips even more—as well as the balancing of market access with the national security concerns of exporting to and servicing ASML equipment in China—are major geopolitical and economic concerns.[b]

a. Mat Honan and James O'Donnell, "How ASML Took Over the Chipmaking Chessboard," *MIT Technology Review*, April 1, 2024, https://www.technologyreview.com/2024/04/01/1090393/how-asml-took-over-the-chipmaking-chessboard/; Charlotte Trueman, "Intel Acquires ASML's Entire 2024 Stock of High NA EUV Machines," *Data Center Dynamics*, May 9, 2024, https://www.datacenterdynamics.com/en/news/intel-acquires-asmls-entire-2024-stock-of-high-na-euv-machines/.

b. Arjun Kharpal, "Netherlands Takes On U.S. Export Controls, Controlling Shipments of Some ASML Machines," CNBC, September 6, 2024, https://www.cnbc.com/2024/09/06/netherlands-expands-export-curbs-on-advanced-chip-tools.html.

The growing influence of the private sector in critical technologies has led US officials to emphasize the need for closer public-private cooperation and government regulation. Even if the government does not lead in innovation, it still plays a crucial role in funding R&D—and especially R&D with lengthy time horizons—promoting key innovations, setting standards, and stimulating the formation of coalitions of private-sector actors domestically and internationally.

The Relationship of Political Regime Type to Technological Progress

National priorities can 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 the country's transition to more democratic rule.

During this time, the global manufacturing landscape for key technologies, particularly semiconductors, underwent significant shifts. Over the past three decades, the US share of global semiconductor production dropped from 37 to 12 percent, as noted in chapter 9, on semiconductors. Meanwhile, Asian manufacturers, especially in South Korea and

Taiwan, have emerged as major players, supported by government policies and regional demand shifts. Asia has 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 it 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. (See the sidebar on extreme ultraviolet and advanced chip fabrication for an example.)

Finally, although genuine technological innovation occurs in both democracies and autocracies, each regime type has different advantages and faces different challenges. Democracies benefit from the rule of law, a free flow of ideas and people, and greater freedom for individuals to pursue their own research interests. Perhaps most importantly, because failure in a democracy should not lead to persecution or professional ostracism, individuals are freer to experiment and explore. By contrast, authoritarian regimes are characterized by the rule of the state and sometimes impose 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 a government considers 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 can; they can also 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 such efforts in the West, which generally has stronger privacy protections against governmental intrusion than China does.

Innovation Pathways and Patterns of Progress

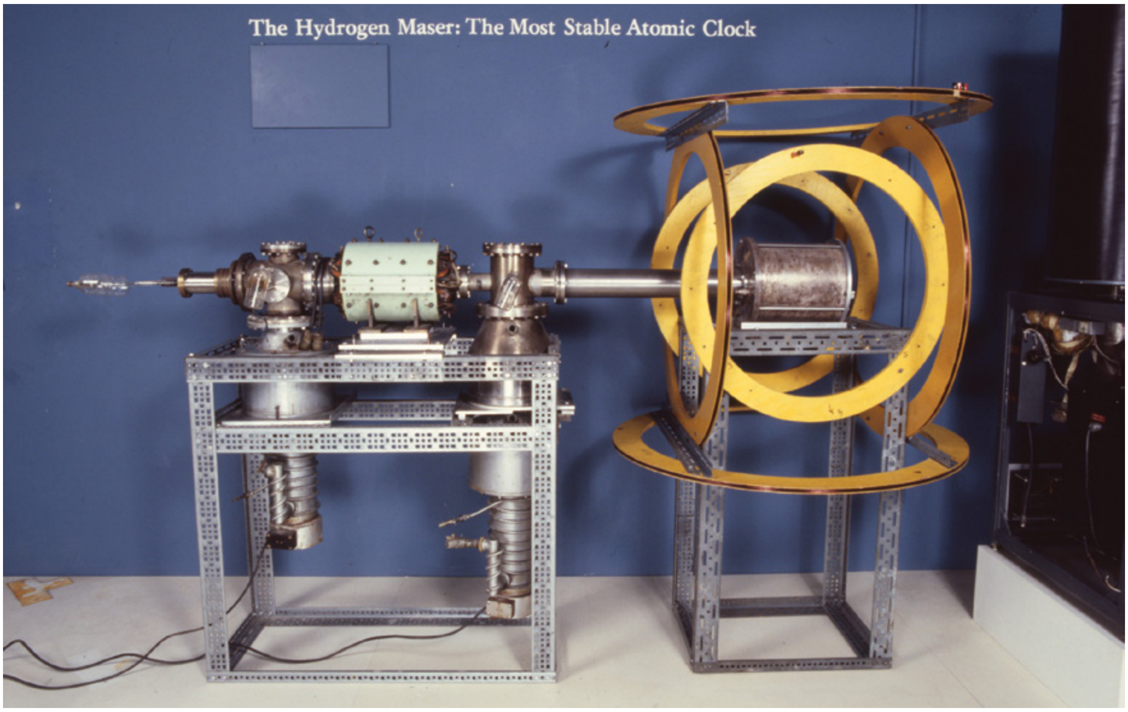
KEY TAKEAWAYS

- Technological progress is often unpredictable and nonlinear, with periods of slow development interrupted by sudden breakthroughs. While some fields, like semiconductors, have shown steady improvement, most technologies advance through cycles of experimentation, feedback, and convergence of multiple innovations.
- Nonscientific factors, such as engineering feasibility, economic viability, manufacturing challenges, and societal acceptance, influence the adoption of technology based on scientific advances.
- Hype can distort perceptions, leading to inflated expectations that outpace practical utility and distortions in resource allocation.
- Frontier bias causes overemphasis on new technologies and sometimes results in overlooking impactful uses of established ones.
- The synergies between different technologies are large and growing, which makes understanding the interactions between different fields all the more important.

The Unpredictable and Nonlinear Nature of Technological Progress

Technological progress exhibits a variety of patterns. For example, progress in semiconductors has been fairly predictable historically, progressing consistently with Moore's law, which predicts a continuing exponential decrease in the cost of computation over time. But, as noted in chapter 9 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

FIGURE 11.1 Norman Ramsey's hydrogen maser, made in 1959–60, known as the "most stable atomic clock," displayed at the Smithsonian's National Museum of American History



Source: The Smithsonian's National Museum of American History, https://americanhistory.si.edu/collections/object/nmah_714239

curves, except that these cost decreases are usually represented as a function of manufacturing experience and expertise rather than of time.[9]

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. For example:

- Timekeeping relied on devices such as sundials and water clocks until the invention of the mechanical clock in the late Middle Ages provided the first significant jump in accuracy.[10] Following a prolonged period of incremental refinement, the introduction of electric clocks—with the frequency of alternating current (AC) from the wall providing a time base—further enhanced the accuracy and reliability of clocks. Subsequent innovations, including quartz and atomic clocks (see figure 11.1), established today's remarkable standards of precision.
- Crop yields have increased only incrementally over time, except during certain periods of rapid innovation associated with technological developments such as synthetic fertilizers, mechanization, high-yield crop varieties, and the rise of biotechnology and precision agriculture.[11] During these periods, crop yields jumped quite substantially, only to resume a pace of gradual improvements as these innovations spread more widely.

- The World Wide Web emerged in the 1990s as a significant development in global communication and information exchange.[12] The web enabled users to access and navigate information through interconnected hypertext links. Used with point-and-click interfaces (also known as browsers), it was rapidly adopted. This led to substantial growth in websites, online communities, and e-commerce and influenced worldwide information accessibility and interaction.

At other times, a surge in innovation is due to the simultaneous availability and maturity of several key technologies that are combined to achieve significant progress in some other technological domain—this is the convergence phenomenon, discussed later in this section.

Predicting future progress can be challenging and misleading due to this pattern of punctuated innovation. Even experts in a given field can be surprised by the rapidity of progress. For instance, Geoffrey Hinton, a pioneer 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.

His comments came after a long history of multiple "AI winters."[13] Enthusiasm for AI in the 1950s and 1960s subsequently led to the first major AI winter (1974–80). The 1980s saw a revival of enthusiasm for AI involving rule-based expert systems, but unmet expectations triggered a second winter in the late 1980s and into the 1990s. Progress inspired by the machine learning approach in the 2000s led to a resurgence in the next two decades. This led to the new surge of enthusiasm and optimism we are witnessing today, which is driven by advances in deep learning, very large datasets, and increases in computing power.

The punctuated nature of most technological change suggests that expectations of regular and rapid evolution in many fields are generally not realized,[14] despite what headlines in the news might lead one to believe. This point is also relevant to another important observation: The traditional linear model of R&D, which envisages smooth progress from basic research to applied research, leading to development and then to marketable products, represents just one way in which societies derive value from technological investments.

Progress also occurs in nonlinear ways that depend on feedback between the various stages of activity. For example, some challenging problems require a deeper fundamental scientific understanding known as "use-inspired basic research," which comes into play after innovations have already been deployed. Research in AI on LLM hallucinations (outputs of entirely false statements) fits into this category. The models are already broadly useful despite such errors occurring frequently. Nevertheless, these hallucinations are problematic, and important research is underway to understand the mechanisms that lead LLMs to generate them.

In other cases, technology convergence can have a big impact on synergy and innovation. Here, convergence means that several distinct technologies have advanced to the point at which they can be integrated to develop a useful innovation. For example, electric cars today are made possible by the convergence of advances in battery technology, lightweight materials, sensors, and computing power. Together, these advances have improved vehicle range, safety, and efficiency and have enabled features like autonomous driving and real-time diagnostics. Another example comes from chapter 6 in this report, on neuroscience, 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.

In short, for most applications, true innovation requires repeated cycles of experimentation, learning, and adaptation rather than a single, direct path. Feedback, convergence, and iteration are the norm, not the exception.

Nonscientific Influences on Innovation

Scientific advances are frequently highlighted 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 an economically viable and societally useful product or service based on the technology.

After achieving scientific proof of concept, a given technology application based on that science must demonstrate engineering practicality. An example is the idea of a chemically fueled, single-stage-to-orbit spacecraft launched from Earth. It is generally believed that launching a spacecraft using a single rocket stage, rather than multiple stages, is just barely possible using current rocket fuels and materials. However, not even a leading company like SpaceX has been able to demonstrate a feasible engineering design that could 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.

Manufacturing comes next. Even if engineering feasibility has been demonstrated, developing a viable manufacturing process to build a product or service based on the initial scientific proof of concept may still prove too difficult. There may be other constraints as well: For instance, materials used to demonstrate engineering feasibility may be too expensive or rare to support large-scale production. (Manufacturing is discussed in more detail later in this chapter.)

Another important factor is the availability of cheaper alternatives to a new technology, which can undermine the commercial viability of the innovation. The competition between lithium-ion (Li-ion) and sodium-ion batteries illustrates this. 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, and work on producing these batteries has driven down their cost signficantly. Thus, the economics of procurement today favor Li-ion batteries in many common applications. However, any significant disruption of the lithium supply chain could make sodium-ion ones more competitive.

Societal acceptability is yet another important nonscientific influence on technological progress. The psychology of individuals, as well as the cultural practices and beliefs of a community or society, influence the adoption and use of any given application of an emerging technology. For instance, producing and consuming GMOs as food is highly controversial in Europe, and concerns over their safety have prevented the uptake there of GMO foods that are consumed widely in the United States.

Finally, the journey from scientific breakthrough to practical, widespread application is often more difficult than anticipated. Innovators may discover that fulfilling promises to investors and customers requires greater resources and longer timelines and delivers fewer benefits or capabilities than expected. Obstacles such as raising adequate funding, navigating environmental or social concerns, and managing risks related to ethics, privacy, and public trust frequently surface only as products or services reach the market. Policymakers, therefore, face the complex challenge of supporting promising advances while being mindful of their associated risks.

Striking the right balance requires acknowledging that disruptive technological progress brings both opportunity and uncertainty. While advocates may downplay early concerns as barriers to the innovations that would benefit their businesses, unaddressed risks—especially ones that could impact society—can escalate as new technologies scale. Governments can mitigate these challenges by incorporating diverse and even critical perspectives early in the technology life cycle, fostering an environment that encourages innovation while managing its potential downsides.

Technological Optimism, Hyperbole, and Technical Reality

This publication highlights ten significant emerging technologies. In preparing the latest edition of the *Stanford Emerging Technology Review* (*SETR*), faculty members from each of these fields expressed broad optimism about the societal and scientific value of research in their respective domains. This optimism is hardly surprising: Those who dedicate their careers to advancing new technologies naturally believe in their potential to address important challenges. Indeed, a conviction that progress will continue and yield solutions is almost a prerequisite for anyone deeply invested in innovation.

However, the line between responsible optimism and irresponsible hype can be crossed easily, leading to an all-too-common pattern where media coverage ignoring basic scientific fundamentals leads to overinflated expectations among the public.

Technological hype often begins with a breakthrough in an emerging technology area, quickly followed by grandiose promises of disruptive, even revolutionary impact. Such promises—in reality, overpromises—make claims that go far beyond what available knowledge and evidence support. They focus on potential rather than proven functionality and often rely on emotional appeal and ambiguous terminology. They also imply that all social or economic challenges can be solved through technological innovation alone, ignoring implementation barriers, regulatory considerations, social acceptance, or the harms often caused by large-scale deployments of unproven technology.

A prominent example of technological hyperbole comes from 1989, when two chemists at the University of Utah announced they had achieved cold fusion—that is, fusion reactions at low temperatures. This finding, if true, would have challenged the scientific consensus that extremely high temperatures are required for such reactions. Rather than following the standard scientific process of peer review, the researchers revealed their findings at a press conference, touting the potential for a clean, virtually inexhaustible energy source.[15] National advisors emphasized the discovery's importance, suggesting that it was too significant to leave solely to the scientific community.[16] The implication was that factors other than science should play an important role in how the nation should proceed at that moment. This was despite the fact that the possibility being discussed (that cold fusion had actually been discovered) was entirely a scientific question.

The scientists' subsequent publication underwent expedited peer review and was widely criticized for lacking essential experimental details, which made independent verification difficult. Their claims rested on observations of heat production that they attributed to fusion. However, later investigations identified significant flaws in their measurement techniques, undermining confidence in their overall findings.

This 1989 episode is widely regarded today as an object lesson in the perils of circumventing the normal processes of science. Some researchers are still working on low-temperature fusion as a plausible mechanism for generating energy, and the field is supported at the level of around $10 million per year in research funding. However, this level of support—a very small fraction of the funding dedicated to more traditional fusion research—should not be regarded as vindication for the original cold fusion proponents. Rather, it reflects the quite modest level of support appropriate for an approach to fusion that is regarded skeptically by most in the scientific community but has not been shown to be categorically false.

Technological hype affects investors, consumers, policymakers, and other stakeholders—all of whom must navigate the complex interplay between marketing rhetoric and substantive advancement. Underlying any given instance of technological hype is often something genuine—some scientific or technological development that is in fact new or noteworthy. But public stakeholders would be well advised to allow the scientific review process to play out before jumping on a hyperbole-driven bandwagon.

Frontier Bias

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 earlier versions of this report—requests for briefings arising from the publications have most often focused on what's newest and most advanced in various fields. Frontier bias emerges from many sources, but one of the most prominent is the technology hype described in the previous section.

Given humans' predilection for novelty, this bias is understandable. But it 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 means of advancing national and societal interests and, by definition, does not rely on fundamental scientific or technological breakthroughs.

One prominent example of older or known technologies being used in such ways can be seen in the present Russia-Ukraine war. Many of the drones having a significant effect on the battlefield 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 using 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; 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 been widely adopted by forces around the world,[17] most notably insurgent groups and terrorists.[18]

The story in chapter 10 on sustainable energy in *SETR* 2025, about a second life for electric vehicle (EV) batteries, is also relevant. As EVs become more prevalent, batteries in them that are coming to the end of their useful life face being discarded. But they often still have significant capacity for power storage. Specialized battery-management systems tailored to these batteries' unique characteristics can help them serve in stationary energy-storage applications (see figure 11.2), such as by acting as

[Frontier] bias is understandable. But it carries with it the risk of overlooking "old" technologies that can be used in novel and impactful ways.

FIGURE 11.2 Advanced battery-management systems being used as stationary storage capacity

Source: Smartville

backup power sources for the grid. Because of their age, they may not be at the cutting edge of battery technology when they are converted, but such systems can give a productive second life to batteries that would otherwise be thrown away.

A second consequence of frontier bias is a misunderstanding of the difference between scientific or technological advances and adoption at scale—a phenomenon that was noted earlier under "nonscientific influences on innovation." 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 in *SETR* 2025, 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 by individuals based on their own personal needs. The rapid spread of personal computers in the 1980s and of rooftop solar panels for home electricity generation in the past decade are examples of people willing to spend money out of their own pockets to derive the benefits of these innovations. The result was rapid uptake and adoption throughout society.

At the other extreme, advanced technology that needs a significant degree of centralized planning or funding for realization is likely to require much longer timescales for widespread adoption. Nuclear energy requires the construction of nuclear reactors that cost billions of dollars. State-of-the-art semiconductor plants cost tens of billions of dollars. 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 to individuals, though it is of use to industrial facilities. For such innovations, it is unrealistic to expect rapid and widespread adoption throughout society.

Large and Growing Synergies Between Different Technologies

The synergies between different technologies are both significant and expanding, as advances in one field often enhance progress in others. For example:

- 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.[19]

- AI helps to screen many candidate compounds to predict the ones most likely to exhibit desirable properties for materials science.[20]

- 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.[21]

- Materials science is important in space research, where the creation of new materials may be needed for the construction of advanced spacecraft and satellites.[22] It is also important in neuroscience, where it enables the development of neural probes that can send and receive electrical signals in neural tissue.[23]

- Energy technologies help to improve the performance of robotics and spacecraft.[24]

- Synthetic biology can build organisms that produce certain specialized materials.[25]

- Cheaper semiconductors have driven down the cost of DNA sequencing, which itself is a fundamental technology for synthetic biology.[26]

This point is more obvious when a field such as AI or materials science is seen as a 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. Less obvious is that AI itself has benefited greatly from advances in semiconductor technology, which has itself benefited from developments in materials science.

In certain instances, a useful technology becomes an enabling technology—a technology whose existence and characteristics enable applications that would not otherwise be feasible or affordable, especially across a number of different fields.[27] (The sidebar on lasers as an enabling technology across multiple sectors, drawn from *SETR* 2025, provides an example.)

An enabling technology can evolve into a general-purpose technology if it becomes broadly useful across many domains. A general-purpose technology is characterized by continuing improvement, wide applicability, and benefits that extend well beyond its original uses. Each advance in a general-purpose technology amplifies its overall impact. Historical examples—such as the steam engine, electricity, and information technology—have transformed economic growth, industry, and daily life. General-purpose technologies ultimately reshape how people, firms, and governments interact with a wide range of other technologies and with one another.

Human Capital and Knowledge Ecosystems

KEY TAKEAWAYS

- Human capital is the foundation of scientific and technological progress. Sustained investment in it is the single most critical factor in ensuring long-term national competitiveness and scientific advancement.

- Universities are central both to high-risk research and to science, technology, engineering, and mathematics (STEM) education. Yet federal R&D funding as a share of GDP has declined, and policy ambiguities hinder international collaboration.

LASERS: AN ENABLING TECHNOLOGY ACROSS MULTIPLE SECTORS

Lasers, as highlighted in the 2025 edition of the *Stanford Emerging Technology Review,* are an enabling technology for a wide array of scientific and industrial fields due to their precision, versatility, and efficiency.

Medicine

- **Surgical precision** Lasers are used to ablate, cut, or vaporize tissue and to clot bodily fluids. Unlike traditional tools such as saws or drills, lasers provide cleaner, more precise cuts, minimizing mechanical and thermal damage to surrounding tissues.
- **Cancer treatment** Lasers can target and destroy subsurface tumors with minimal harm to healthy tissue, offering less invasive alternatives for certain procedures.

Military applications

- **Directed-energy weapons** Lasers are being developed as weapons capable of disabling satellites and providing short-range air defense against drones, rockets, and artillery.
- **Target designation** Lasers play a crucial role in guiding munitions by marking targets with beams of light, allowing for highly accurate strikes.

Communications

- **Fiber-optic data transmission** Lasers transmit vast amounts of data through fiber-optic cables. Advances now allow for much shorter laser pulses, maintaining data fidelity while potentially reducing power consumption.
- **Satellite links** Lasers enable high-speed, long-range data transmission between satellites, supporting global communications infrastructure.

Manufacturing

- **3-D printing** Lasers are integral to additive manufacturing techniques such as stereolithography and selective laser sintering. In stereolithography, ultraviolet lasers cure photosensitive resin layer by layer, while in selective laser sintering, lasers fuse powdered materials like nylon or metal. These methods allow for rapid prototyping and the creation of complex structures from various materials.

Imaging

- **X-ray free-electron lasers (XFELs)** XFELs generate powerful X-ray pulses that penetrate materials, enabling high-resolution imaging and measurement of physical properties. Their short wavelengths provide superior spatial resolution compared to visible light, facilitating breakthroughs such as imaging new proteins, observing quantum material phase transitions, and tracking biomolecular movements in real time.

- The "valley of death" between research feasibility and commercial viability remains a major barrier to advancing innovations to market. New funding models are needed to bridge this gap and sustain America's technological leadership.

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

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 nurtured domestically or acquired from foreign sources.

Workers of US origin still make up the majority of the US STEM workforce, although foreign-born talent accounts for an increasingly large fraction of it. 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.[28] Correlation is not causation, but the connection is unlikely to be accidental or spurious.

- Second, other nations—such as China and India, from which significant numbers of STEM students in the United States originate—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 created by such investment 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. Foreign countries may also take steps that explicitly discourage their scientists and engineers from studying or working in the United States.

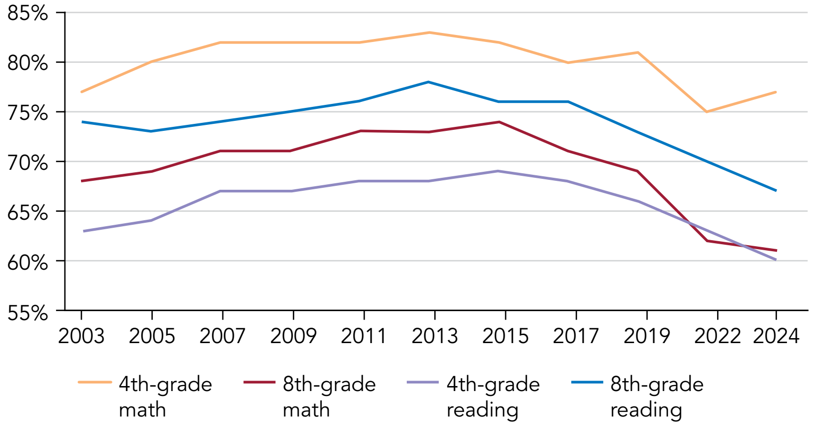
- Third, many security-sensitive jobs depend on US citizens. In 2021, the US Department of Defense (DOD) noted that improving the capacity and resilience of the defense industrial base requires more workers trained in STEM.[29] It also observed that the dearth of trained software engineers working on classified projects was in part because of the requirement that they are US citizens. In 2025, the aerospace and defense sector continued to face a severe talent shortfall, with industry analysts estimating that about fifty thousand software and technology positions remain unfilled.[30]

According to analysts from the National Defense Industrial Association's Emerging Technologies Institute and the Institute for Progress,[31] the US defense industrial base relies on roughly 110,000 foreign-born STEM graduates at any given time; of this number, 85 percent are naturalized citizens. As they conclude, "[US] Defense Department projects are disproportionately likely to turn to international talent [i.e., talent from foreign sources] for advanced STEM skills."

In promoting a more robust domestic contribution to building STEM expertise in America, it is sobering to realize that the United States is also facing a decades-long decline in K–12 (kindergarten to twelfth grade) STEM proficiency,[32] with standardized testing revealing declining scores in fourth- and eighth-grade mathematics.[33] While COVID-19 disruptions account for some of the decline,[34] the 2024 National Assessment of Educational Progress (released in January 2025) shows that US math scores remain below pre-pandemic levels (as seen in figure 11.3): Fourth-grade math scores have risen since 2022 but were still below their 2019 level, while eighth-grade math scores dropped compared with 2019. Reading scores fell from 2019 levels for both grades.[35] This follows a twenty-year trend of diminishing US K–12 STEM proficiency.[36]

Another data point is found in the five-year trend from the national ACT (American College Testing) test, a curriculum-based assessment of high school seniors tracking the mastery of college-readiness standards.[37]

FIGURE 11.3 National Assessment of Educational Progress scores over time



Source: National Assessment of Educational Progress

Since 2020, scores on the college-readiness benchmarks for mathematics and science have dropped monotonically. In 2024, only 29 percent of seniors met the readiness standard for mathematics, and only 30 percent met the standard for science, highlighting a critical educational challenge for the nation's economic and technological competitiveness.

Of particular concern is that only 7 percent of American teens scored in the highest level of math proficiency as measured in 2022 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 is compared to 12 percent of Canadians and 41 percent of Singaporean teens scoring in the top category.[38]

Adding to the challenge is a shortage of qualified STEM educators in the United States. Even as early as 2012, about 30 percent of math teachers, 26 percent of biology teachers, and 54 percent of physical science teachers lacked a major or degree relevant to their teaching assignment,[39] and there is no reason to believe that the situation has improved since then. Further, one study from 2021 estimates the shortage of qualified STEM teachers in middle and high school at between 180,000 and 350,000.[40] Simultaneously, the annual production of new STEM teachers in America has declined, falling from about 31,000 a decade ago to roughly 20,000 today.[41]

When considering foreign sources of STEM talent, immigration policies affecting the labor force can make it harder to meet recruitment goals in industries like semiconductors, biotechnology, and sustainable energy. Foreign talent makes critical contributions to US STEM.

R&D funding levels are also changing. 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 benefit from ideas developed abroad when they read 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. They also offer a deeper understanding of foreign scientific progress. (See the sidebar on the importance of tacit knowledge for more information.)

This point about the importance of tacit knowledge in scientific advancement has been made by many scholars,[42] and it was expressed particularly strongly 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.[43] More generally, drawing from a broader pool of people will yield higher quality talent than digging more deeply into an existing pool simply because the broader pool is more likely to have a greater number of individuals at the high end of the talent distribution.

THE IMPORTANCE OF TACIT KNOWLEDGE

Tacit knowledge is almost always found at the frontiers of new technologies. Unlike explicit knowledge, which can be codified and shared in documents, tacit knowledge consists of personal, intuitive skills and insights gained through experience and practice that are hard to articulate. Such knowledge allows practitioners to interpret results, troubleshoot equipment, and apply theories effectively—skills that cannot be fully acquired from published papers alone. Instead, these abilities often require working alongside experienced professionals and absorbing problem-solving habits through direct interaction.

The significance of tacit knowledge is clear even outside the laboratory. For example, in the semiconductor sector, close on-site collaboration between chip buyers and manufacturers helps minimize production downtime since diagnosing problems often depends on hands-on familiarity with complex equipment. Some semiconductor companies even embed technicians with their customers worldwide because the technicians' subtle skills at equipment calibration cannot be captured in manuals; rather, they must be conveyed through mentorship and direct, hands-on involvement.

As a technology matures, the tacit knowledge of experts in the field becomes more explicit. This shift signals progress: For any technology to be integrated into a society's infrastructure, informal know-how must be documented and standardized. Turning these unspoken practices into clear procedures and guidance supports wider adoption and also ensures that a technology can be taught, replicated, and relied upon by a broader group of practitioners. This transformation—from personal mastery to public instruction—marks the transition from a niche innovation to a stable, essential technology.

US policies that discourage immigration can reduce the influx of skilled workers, impacting the country's capacity for innovation.[44] They also shift skilled talent and multinational R&D investment to other countries, including strategic competitors such as China and also close allies such as Canada.[45] This shift can sometimes force US companies to relocate abroad due to worker shortages.[46]

Finally, many academic researchers are immigrants on student visas. STEM workers educated in the United States are more likely to have personal and, in many cases, citizenship loyalties to America and can fairly be regarded as more likely to remain in the country than to leave after completing their studies. But without offering them a clear route to permanent residence, the United States loses key teaching and research talent in vital STEM domains.

Today, both domestic and foreign 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 blunt, widespread cuts in opportunities for collaboration with foreign scientists when a surgical scalpel could be used to address only the issues warranting serious concern is a sure way to undermine the effectiveness of US scientific endeavors.

Role of Universities in Technological Innovation

Within the innovation ecosystem, universities play two unique and pivotal roles that are often underappreciated. First, they have the mission of pursuing high-risk research openly that may not pay off in commercial or societal applications for a long time, if ever.[47] (See the sidebar on the long-term reach of university research for some examples.) This openness accelerates discovery by making study details, data, and results accessible to others. Private companies contribute to the innovation process, but universities and other research institutions are key to many advancements. 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.[48] University openness magnifies educational and societal benefits by enabling other researchers to build on prior work, thus driving innovation forward.

Second, as educational institutions, universities play the central role in developing STEM expertise within the next generation. Any long-term plan for STEM leadership globally must include efforts to sustain advantages that the United States has. For example, 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 can create an environment where the next generation of STEM leaders will 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 has created new industries and jobs, spurred economic growth, and supported a high standard of living while also achieving national goals for defense, health, and energy.[49] 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 R&D funding from all sources grew significantly in 2023, reaching $108.8 billion—an 11.2 percent increase from 2022[50] (though it is likely to now be significantly lower given recent funding cuts). 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 on commercial viability.[51] 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. Nevertheless, the proportion of academic R&D funding supported by the US government declined over the past decade, standing at 55 percent of total support for academic R&D in 2023, the most recent year with available data.[52]

As a percentage of GDP, funding trends have also been 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 fallen from 1.86 percent of GDP in 1964 to just 0.63 percent of GDP in 2022.[53]

Until 2025, a constrained budget environment was the primary driver of these negative funding trends. For example, the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act of 2022 authorized dramatically increased funding for basic research—about $53 billion—but Congress provided only $39 billion in the corresponding appropriation.[54] 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.[55]

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. (A perceptron is the simplest form of neural network; it has one layer of artificial neurons.) Although this line of research was abandoned after a decade or so, it ultimately gave rise to the work on deep learning in artificial intelligence several decades later.

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

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.

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 they 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-American 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.

Finally, it is true that the US R&D landscape is vast, with major contributions from both private industry and the federal government. Historically, private research centers like Bell Labs and IBM's Thomas J. Watson Research Center advanced foundational science. However, most corporate R&D today is focused on applied, proprietary work with limited accessibility. Federal labs and other government-backed research facilities, such as those run by the US Department of Energy (DOE), DOD, and NASA, tackle complex, mission-specific challenges. But the research undertaken in the private sector and federal laboratories does not substitute for university research: Unlike mission-driven federal labs, universities pursue a broad range of research topics, and unlike the private sector, they emphasize open, transparent research that fosters accountability, collaboration, and wide-reaching impact.

The Structure of Research and Development Funding

The scale of investment that nations make in R&D matters, but it is also critical how that money is allocated. 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 after the engineering feasibility of an innovation has been demonstrated but before large-scale adoption and commercial viability has been achieved, is a significant problem.

That valley exists because when a new innovation is first offered to customers, its cost relative to what it is capable of can be a deterrent to adoption. High initial costs can put off 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 reach this point must first find ways to scale their activities to demonstrate their innovations' capabilities at scale—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 if those 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 of development, 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 it is an ongoing challenge to distinguish between genuinely promising innovations and those that appear to be innovative but are not commercially viable. Firms failing to cross the valley of death could be acquired by foreign competitors from China and other nations with a greater willingness to invest in a technology not yet proven in the marketplace.

Focused research organizations (FROs) are a new nonprofit funding model designed to bridge the valley of death by providing financial support to teams of scientists and engineers for rapid prototyping and testing of technologies that advance the public good. Convergent Research, a nonprofit established in 2021 to support FROs, received $50 million in philanthropic donations in March 2023 to start two new FROs.[56]

Infrastructure for Innovation

KEY TAKEAWAYS

- Standards enable interoperability, lower costs, and support global trade, but they can also stifle innovation and be manipulated for market control or geopolitical advantage.
- Manufacturing is vital for economic resilience and security, especially amid global supply chain disruptions and strategic competition with China and other nations. Technological advances like robotics and AI are reshaping production, while policies such as the CHIPS and Science Act of 2022 aim to boost domestic capacity.
- Cybersecurity protects data, systems, and intellectual property from threats, ensuring research integrity and confidentiality. However, maintaining robust security can conflict with the open culture of research environments.

Standards

Standards are agreements—often formal ones—that specify technical or other requirements for products, processes, or services. Their primary function is to ensure that different systems and components are interoperable (i.e., they can work together effectively). Examples include standardized shipping containers, which revolutionized global logistics, and universal information technology protocols, like Universal Serial Bus (USB) and internet-related standards, which facilitate a high degree of compatibility across devices and networks.

Standards play a key role in enabling the diffusion of new technologies and are a foundational element of modern economies. They provide common frameworks that facilitate interoperability, compatibility, and safety, which are essential for scaling innovations from isolated prototypes to widespread adoption. However, while standards offer significant benefits, they also present challenges, including potential constraints on innovation, market power imbalances, and geopolitical complexities.

Research has shown that standards lower transaction costs, reduce uncertainty for producers and consumers, and enable the creation of large, interconnected markets.[57] Also, by codifying knowledge and best practices through consensus-based processes, they often play an important role in transforming scientific discoveries into commercial technologies, products, and services.[58] Standards streamline coordination by minimizing ambiguity in performance expectations and by supporting interoperability, which in turn accelerates market uptake.

Another key function of standards is to foster trust. Quality and safety standards mitigate the risks associated with innovative products, reducing uncertainty and bridging information gaps between developers and users.[59] Such trust facilitates early adoption and can contribute to the success of new technologies in the marketplace. For example, in the 1980s and 1990s, Europe's early adoption of the Global System for Mobile Communications (GSM) standard enabled rapid technical development, swift deployment, and seamless cross-border roaming, helping Europe quickly become a global telecom leader.

Overall, the economic impact of standards is substantial. Empirical studies across countries such as Germany, France, Australia, the United Kingdom, and Canada estimate that standards contribute between 0.2 and 0.9 percent to annual GDP growth.[60] They can also play a strategic role in national competitiveness. Countries that actively participate in international standard-setting bodies can influence the direction of technological development and ensure that their domestic industries are well positioned in global markets.

While they provide many benefits, standards also present challenges, including potential constraints on innovation, market power imbalances, and geopolitical complexities. One often-expressed concern is that prematurely deploying a set of standards may stifle innovation by locking in a particular technology or approach, making it difficult for newer, radically different, and potentially superior solutions to gain traction.

For example, the widespread use of the QWERTY keyboard—originally designed for mechanical typewriters in the nineteenth century—continues despite well-documented evidence that alternative layouts are significantly easier to learn and allow faster typing. The main reason the QWERTY layout remains dominant is that switching to another layout is seen as too costly for individuals and organizations.

Furthermore, the standardization process is often time and resource intensive, and dominant firms may use their influence to ensure standards favor their proprietary technologies, raising rivals' costs and creating barriers to entry. This can lead to market concentration, reduced competition, and the risk of industries becoming locked into aging solutions.

This history of "standards wars" between incompatible technologies illustrates how, when no clear standard prevails, competing standards can fragment markets and slow global diffusion.[61] The videotape format war between VHS (Video Home System) and Betamax in the late 1970s into the 1980s is a classic example. Betamax had better picture quality but shorter recording times, higher costs, and restrictive licensing. VHS offered longer recording times, lower prices, and open licensing, attracting more manufacturers and broader studio support. For years, both formats coexisted, forcing consumers and retailers into incompatible ecosystems. VHS's advantages eventually secured dominance, thus forcing Betamax users to convert to VHS and to lose their original investments.[62]

Finally, standardization is increasingly entangled with global geopolitical competition, as countries vie for influence in international standards bodies to shape rules that favor domestic firms. This can lead to the emergence of competing standards regimes, undermining global interoperability and raising the complexity and cost of doing business internationally.

Manufacturing

Manufacturing plays an increasingly critical role in the US economy and national security, driven by a rapidly evolving geopolitical landscape and the growing recognition of vulnerabilities in global supply chains. Strategic competition with China has intensified US

This history of "standards wars" between incompatible technologies illustrates how . . . competing standards can fragment markets and slow global diffusion.

concerns over economic security and technological leadership, especially as China advances in semiconductors, AI, and clean energy. Partly in response, the United States is prioritizing domestic manufacturing to reduce reliance on foreign sources and to better protect critical technologies.[63]

Recent global events, such as the COVID-19 pandemic and increased use of export restrictions, have exposed the fragility of international supply chains and revealed how disruptions abroad can have immediate and severe impacts on the availability of essential goods in the United States. This has led policymakers and industry leaders to focus on expanding domestic production capacity and achieving greater technological self-sufficiency.

On the supply side, technology innovation is driving a manufacturing renaissance. Advances in robotics, AI, additive manufacturing (3-D printing), advanced materials (see chapter 5, on materials science), and big data analytics are transforming how goods are designed, produced, and delivered. These technologies enable greater customization, faster prototyping, and more efficient production. Automation and AI may also offset labor cost advantages that previously favored offshoring.

Manufacturing is closely linked to national security. A strong domestic manufacturing base would ensure that the United States can produce critical defense systems at significant scale, maintain technological superiority, and respond to emerging threats. It would also reduce risks such as espionage, intellectual property theft, and supply chain subversion that are often associated with foreign manufacturers. Additionally, manufacturing supports millions of jobs, drives innovation, and stabilizes supply chains across the economy.

Revitalizing US manufacturing is a prospect that enjoys bipartisan support. For example, under the Biden administration, the CHIPS and Science Act was passed in 2022. It was intended to return a significant amount of chip fabrication to American shores. Similarly, the Trump administration's Made in America Manufacturing Initiative is intended to encourage and enable domestic manufacturers—especially small and midsize firms—to become preferred suppliers for government contracts, particularly in critical sectors like aerospace, defense, and energy.

Cybersecurity

Cybersecurity encompasses the technologies, processes, and policies that protect computer systems, networks, and the information they contain from malicious activities by adversaries or unscrupulous actors. The field centers on the protection of three core principles: 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. As the internet expanded, and networked devices proliferated, the scope of cybersecurity broadened to include the protection of infrastructure that supports data transmission and storage. The field has since evolved to address new challenges, including social engineering attacks, digital misinformation, information warfare, and the risks posed by AI at both the human and system levels. (The development and use of foundational AI models introduce additional cybersecurity risks, as discussed in chapter 3, on cryptography and computer security.)

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. In research settings, one major concern is ensuring the integrity of scientific data. The deletion, destruction, or subtle alteration of research data can undermine scientific progress by wasting resources or undermining the validity of results. Computer programs used in research are similarly vulnerable; minor, undetected changes in them can call into question the accuracy of previously collected or analyzed data.

Protecting the confidentiality of work products—such as datasets and draft working papers—is equally important. Unauthorized access to confidential datasets can breach agreements and compromise academic integrity, while premature disclosure of draft research can undermine claims of priority and reveal incomplete or inconsistent findings. Computers that manage laboratory data collection are susceptible to attacks that could disrupt research continuity by corrupting data or damaging equipment.

While technical safeguards exist to address these cybersecurity challenges, maintaining them in academic settings requires substantial management effort. The informal, collegial, and flexible culture common in research labs often views rigorous security practices as disruptive, which can lead to resistance to them or to inconsistent implementation.

Another growing threat involves the selective targeting of personnel working on key research projects. Researchers may face cyber harassment, financial compromise, or threats to family members. Attacks on professional ethics through social media or online forums can damage reputations, cause personal distress, and reduce productivity.

Addressing these multifaceted cybersecurity challenges requires a careful balance between robust protection and the need for open, collaborative research environments. Effective cybersecurity policies and practices must be adaptable, recognizing the unique risks and cultural dynamics present in academic and research settings while ensuring the integrity, confidentiality, and availability of critical information and systems.

NOTES

1. See, for example, Josh Luckenbaugh, "Just In: U.S. Falling Behind China in Critical Tech Race, Report Finds," *National Defense*, July 17, 2023, https://www.nationaldefensemagazine.org/articles/2023/7/17/us-falling-behind-china-in-critical-tech-race-report-finds; Jeremy Neufeld, *STEM Immigration Is Critical to American National Security* (Institute for Progress, 2022), https://ifp.org/stem-immigration-is-critical-to-american-national-security/; Craig Cohen and Alexander Kisling, eds., "Part II: Winning the Economic and Tech Race," in *2024 Global Forecast: A World Dividing* (Center for Strategic and International Studies, 2024), https://csis-website-prod.s3.amazonaws.com/s3fs-public/2024-01/240130_GlobalForecast_2024_WinningEconomic_TechRace.pdf.

2. International Monetary Fund, "Is Productivity Growth Shared in a Globalized Economy?," chap. 4 in *World Economic Outlook 2018: Cyclical Upswing, Structural Change* (April 2018), https://www.imf.org/en/Publications/WEO/Issues/2018/03/20/world-economic-outlook-april-2018.

3. Catherine Tucker, "Network Effects and Market Power: What Have We Learned in the Last Decade?," *Antitrust*, 2018, 72–9.

4. See, for example, Manuel Hoffmann, Frank Nagle, and Yanuo Zhou, "The Value of Open Source Software," Harvard Business School Strategy Unit Working Paper no. 24-038, https://doi.org/10.2139/ssrn.4693148.

5. Davide Rigo, "Global Value Chains and Technology Transfer: New Evidence From Developing Countries," *Review of World Economics* 157 (2021): 271–94, https://doi.org/10.1007/s10290-020-00398-8.

6. Commission on the Theft of American Intellectual Property, "IP Commission 2021 Review: Updated Recommendations" (2021), https://www.nbr.org/wp-content/uploads/pdfs/publications/ip_commission_2021_recommendations_mar2021.pdf.

7. Pamela Samuelson and Suzanne Scotchmer, "The Law and Economics of Reverse Engineering," *Yale Law Journal* 111, no. 7 (2002):1575–1663, https://www.yalelawjournal.org/article/the-law-and-economics-of-reverse-engineering.

8. Adam Satariano et al., "Elon Musk's Unmatched Power in the Stars," *New York Times*, July 28, 2023, https://www.nytimes.com/interactive/2023/07/28/business/starlink.html.

9. On solar panels, see François Lafond, Aimee Gotway Bailey, Jan David Bakker, et al., "How Well Do Experience Curves Predict Technological Progress? A Method for Making Distributional Forecasts," *Technological Forecasting and Social Change* 128 (2018): 104–17, https://doi.org/10.1016/j.techfore.2017.11.001. On LEDs, see Brian F. Gerke, Allison T. Ngo, Andrea L. Alstone, and Kibret S. Fisseha, *The Evolving Price of Household LED Lamps: Recent Trends and Historical Comparisons for the US Market*, Office of Science and Technical Information (US Department of Energy, 2014), https://doi.org/10.2172/1163956.

10. "A Walk Through Time—A Revolution in Timekeeping," National Institute of Standards and Technology, August 12, 2009, https://www.nist.gov/pml/time-and-frequency-division/popular-links/walk-through-time/walk-through-time-revolution.

11. Keith Fuglie, Madhur Gautam, Aparajita Goyal, and William F. Maloney, *Harvesting Prosperity: Technology and Productivity Growth in Agriculture* (World Bank, 2020), https://openknowledge.worldbank.org/bitstreams/3621191c-15f3-5ede-a89c-f7190d7e1dba/download.

12. “History of the Web,” World Wide Web Foundation, October 18, 2009, https://webfoundation.org/about/vision/history-of-the-web/.

13. Amirhosein Toosi, Andrea Bottino, Babak Saboury, Eliot Siegel, and Arman Rahmim, “A Brief History of AI: How to Prevent Another Winter (a Critical Review),” *PET Clinics* 16, no. 4 (2021): 449–69, https://doi.org/10.1016/j.cpet.2021.07.001.

14. See, for example, Vaclav Smil, “Techno-Optimism, Exaggerations and Realistic Expectations,” in *Invention and Innovation: A Brief History of Hype and Failure* (MIT Press, 2023).

15. University of Utah, “‘Simple Experiment’ Results in Sustained N-Fusion at Room Temperature for First Time,” news release, March 23, 1989, archived at https://newenergytimes.com/v2/archives/UofUtah/19890323-Univ-Utah-Press-Release.pdf.

16. For example, Ira Magaziner, paraphrased by author Gary Taubes in Gary Taubes, *Bad Science: The Short Life and Weird Times of Cold Fusion* (Random House, 1993).

17. Stephan Wilkinson, “How the AK-47 Became the ‘Weapon of the Century,” *Military Times*, December 12, 2017, https://www.militarytimes.com/off-duty/gearscout/2017/12/12/how-the-ak-47-became-the-weapon-of-the-century/.

18. Audrey Cronin, *Power to the People: How Open Technological Innovation Is Arming Tomorrow’s Terrorists* (Oxford University Press, 2020).

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

20. This report, chapter 5, on materials science.

21. 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.

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

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

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

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

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

27. A report from the National Research Council of the US National Academies of Sciences, Engineering, and Medicine addresses this distinction in more detail, drawing distinctions between “foundational technologies” and “technology applications,” with the latter focusing on solving specific problems through an artful blend of technologies. Space and robotics are examples of technology applications that build on foundational advances in many fields. See Jean-Lou Chameau, William F. Ballhaus, and Herbert Lin, eds., *Emerging and Readily Available Technologies and National Security: A Framework for Addressing Ethical, Legal, and Societal Issues* (National Academies Press, 2014), https://doi.org/10.17226/18512.

28. See, for example, Maja Bacovic, Zivko Andrijasevic, and Bojan Pejovic, “STEM Education and Growth in Europe,” *Journal of the Knowledge Economy* 13 (2022): 2348–71, https://doi.org/10.1007/s13132-021-00817-7.

29. US Department of Defense, *Industrial Capabilities Report to Congress: 2020 Annual Report* (January 2021), https://www.businessdefense.gov/docs/resources/USA002573-20_ICR_2020_Web.pdf.

30. Eric Chewning, Matt Schrimper, Andy Voelker, and Brooke Weddle, “Debugging the Software Talent Gap in Aerospace and Defense,” McKinsey & Company, July 11, 2022, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/debugging-the-software-talent-gap-in-aerospace-and-defense.

31. Wilson Miles and Jeremy Neufeld, “U.S. Needs International Talent to Maintain Tech Leadership,” *National Defense Magazine*, April 14, 2025, https://www.nationaldefensemagazine.org/articles/2025/4/14/us-needs-international-talent-to-maintain-tech-leadership.

32. Gabrielle Athanasia and Jillian Cota, “The U.S. Should Strengthen STEM Education to Remain Globally Competitive,” Center for Strategic and International Studies, April 1, 2022, https://www.csis.org/blogs/perspectives-innovation/us-should-strengthen-stem-education-remain-globally-competitive; Darrell M. West, “Improving Workforce Development and STEM Education to Preserve America’s Innovation Edge,” Brookings Institution, July 26, 2023, https://www.brookings.edu/articles/improving-workforce-development-and-stem-education-to-preserve-americas-innovation-edge/; Julia Yoon, “Innovation Lightbulb: Strengthening K–12 STEM Education for a Robust U.S. Technology Workforce,” Center for Strategic and International Studies, June 28, 2024, https://www.csis.org/analysis/innovation-lightbulb-strengthening-k-12-stem-education-robust-us-technology-workforce.

33. National Science Board, *Talent Is the Treasure: Who Are We Leaving on the Bench?*, report no. NSB-2024-11 (March 2024), https://www.nsf.gov/nsb/publications/2024/2024_policy_brief.pdf.

34. National Science Board, *Talent Is the Treasure*; Yoon, “Innovation Lightbulb.”

35. Grace Zichelli, “New Issue Brief: 2024 NAEP Results Are a Wake-up Call for American Education,” Manhattan Institute, news release, May 15, 2025, https://manhattan.institute/article/new-issue-brief-2024-naep-results-are-a-wake-up-call-for-american-education.

36. Athanasia and Cota, “The U.S. Should Strengthen STEM Education”; Steven Deitz and Christina Freyman, *The State of U.S. Science and Engineering 2024*, National Science Board, Science and Engineering Indicators (National Science Foundation, 2024), https://ncses.nsf.gov/pubs/nsb20243/; Yoon, “Innovation Lightbulb”; National Science Board, *Talent Is the Treasure*.

37. Table 1.1 in *The ACT: Profile Report—National, Graduating Class 2024*, ACT, https://www.act.org/content/dam/act/unsecured/documents/2024-act-national-graduating-class-profile-report.pdf.

38. Program for International Student Assessment, “PISA 2022 Mathematics Literacy Results,” Institute of Education Sciences,

National Center for Education Statistics, accessed September 18, 2024, https://nces.ed.gov/surveys/pisa/pisa2022/mathematics/international-comparisons/.

39. Tuan D. Nguyen, "The Supply and Quality of STEM Teachers," *Humanities and Social Sciences Communications* 12, no. 1 (2025), https://doi.org/10.1057/s41599-025-04648-8. Though published in 2025, this paper cites other work whose original data provenance dates to 2011–12.

40. Michael Marder, "How Bad Is the U.S. STEM Teacher Shortage?" *Medium*, December 8, 2021, https://uteachinstitute.medium.com/u-s-stem-teacher-shortages-in-2017-2018-1d8314a93ba1.

41. Marder, "How Bad Is the U.S. STEM Teacher Shortage?"

42. Michael Polyani, *Personal Knowledge* (University of Chicago Press, 1962); Thomas S. Kuhn, *Structure of Scientific Revolutions*, 2nd ed. (University of Chicago Press, 1970); for more recent discussions, see: Vincent-Wayne Mitchell, William S. Harvey, and Geoffrey Wood, "Where Does All the 'Know How' Go? The Role of Tacit Knowledge in Research Impact," *Higher Education Research & Development* 41, no. 5 (2022): 1664–78, https://doi.org/10.1080/07294360.2021.1937066; Tim Thornton, "Tacit Knowledge as the Unifying Factor in Evidence Based Medicine and Clinical Judgement," *Philosophy, Ethics, and Humanities in Medicine* 1, no. 2 (2006), https://doi.org/10.1186/1747-5341-1-2.

43. Shai Bernstein, Rebecca Diamond, Abhisit Jiranaphawiboon, Beatriz Pousada, and Timothy McQuade, "The Contribution of High-Skilled Immigrants to Innovation in the United States," Research Briefs in Economic Policy no. 350, Cato Institute, September 20, 2023, https://www.cato.org/research-briefs-economic-policy/contribution-high-skilled-immigrants-innovation-united-states; Jennifer Hunt and Marjolaine Gauthier-Loiselle, "How Much Does Immigration Boost Innovation?," *American Economic Journal: Macroeconomics* 2, no. 2 (2010): 31–56, https://doi.org/10.1257/mac.2.2.31.

44. Dany Bahar et al., "*Talent Flows and the Geography of Knowledge Production: Causal Evidence from Multinational Firms*," Harvard Business School Technology and Operations Mgmt. Unit Working Paper no. 22-047 (December 2022), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4005693.

45. Immigration, Refugees, and Citizenship Canada, "Canada's Tech Talent Strategy," Government of Canada, last modified June 27, 2023, https://www.canada.ca/en/immigration-refugees-citizenship/news/2023/06/canadas-tech-talent-strategy.html.

46. Britta Glennon and David R. Dollar, *Dollar & Sense*, podcast, "What's Behind the Globalization of R&D?," Brookings Institution, April 26, 2021, MP3 Audio, 25:02, https://www.brookings.edu/articles/whats-behind-the-globalization-of-rd.

47. National Academies of Sciences, Engineering, and Medicine, *Information Technology Innovation: Resurgence, Confluence, and Continuing Impact* (National Academies Press, 2020), https://doi.org/10.17226/25961.

48. Neil C. Thompson, Shuning Ge, and Yash M. Sherry, "Building the Algorithm Commons: Who Discovered the Algorithms That Underpin Computing in the Modern Enterprise?," *Global Strategy Journal* 11, no. 1 (2021): 17–33, https://doi.org/10.1002/gsj.1393.

49. National Research Council, *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security* (National Academies Press, 2012), https://doi.org/10.17226/13396.

50. Graham Andrews, "New Data Show Universities Are Increasing R&D Activity," Association of American Universities, December 6, 2024, https://www.aau.edu/newsroom/leading-research-universities-reportnew-data-show-universities-are-increasing-rd-activity.

51. James Manyika and William McRaven, *Innovation and National Security: Keeping Our Edge*, Independent Task Force Report, no. 77 (Council on Foreign Relations, 2019), 21, https://www.cfr.org/report/keeping-our-edge/pdf/TFR_Innovation_Strategy.pdf.

52. Andrews, "New Data Show Universities Are Increasing R&D Activity."

53. National Center for Science and Engineering Statistics, "Long-Term Trends Show Decline in Federally Funded R&D as a Share of GDP While Business-Funded R&D Increases as a Share of GDP," NSF 25-334 (US National Science Foundation, 2025), https://ncses.nsf.gov/pubs/nsf25334.

54. James Pethokoukis, "Broken Promises: CHIPS Act Funding for Science Research Falls Short," *Faster, Please!*, American Enterprise Institute, March 13, 2024, https://www.aei.org/articles/broken-promises-chips-act-funding-for-science-research-falls-short/.

55. Organisation for Economic Co-operation and Development, "OECD Data Explorer: Gross Domestic Expenditure on R&D by Sector of Performance and Type of R&D," 2024, https://data-explorer.oecd.org/vis?fs[0]=Topic%2C1%7CScience%252C%20technology%20and%20innovation%23INT%23%7CResearch%20and%20development%20%28R%26D%29%23INT_RD%23&pg=0&fc=Topic&bp=true&snb=18&vw=tb&df[ds]=dsDisseminateFinalDMZ&df[id]=DSD_RDS_GERD%40DF_GERD_TORD&df[ag]=OECD.STI.STP&df[vs]=1.0&dq=CHN%2BUSA.A.._T...BR...USD_PPP.Q&pd=2012%2C2021&to[TIME_PERIOD]=false. Analysis conducted by comparing two methods of measuring annual increases of US and China spending on basic research and projecting rates into future.

56. Alex Knapp, "Why Billionaires Ken Griffing and Eric Schmidt Are Spending $50 Million on a New Kind of Scientific Research," *Forbes*, March 17, 2023, https://www.forbes.com/sites/alexknapp/2023/03/17/why-billionaires-ken-griffin-and-eric-schmidt-are-spending-50-million-on-a-new-kind-of-scientific-research.

57. G. M. Peter Swann, *The Economics of Standardization: An Update*, report for the UK Department of Business, Innovation and Skills (Innovative Economics Limited, 2010), https://assets.publishing.service.gov.uk/media/5a790abd40f0b679c0a0812d/10-1135-economics-of-standardization-update.pdf.

58. European Commission, "A strategic vision for European standards: Moving forward to enhance and accelerate the sustainable growth of the European economy by 2020" (Communication) COM (2011) 0311 final, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0311:FIN:en:PDF.

59. *Building Trust: The Conformity Assessment Toolbox*, International Organization for Standards, 2023, https://www.iso.org/files/live/sites/isoorg/files/archive/pdf/en/casco_building-trust.pdf.

60. Andre Jungmittag and Axel Mangelsdorf, *The Economic Benefits of Standardization*, DIN German Institute for Standardization, 2011, https://www.din.de/resource/blob/89552/68849fab0eeeaafb56c5a3ffee9959c5/economic-benefits-of-standardization-en-data.pdf.

61. Carl Shapiro and Hal R. Varian, "The Art of Standards Wars," *California Management Review* 41, no. 2 (1999): 8–32, https://doi.org/10.2307/41165984.

62. Brad Kelechava, "VHS vs Betamax: Standard Format War," *The ANSI Blog*, May 5, 2016, https://blog.ansi.org/ansi/vhs-vs-betamax-standard-format-war/.

63. "The CHIPS Act: What It Means for the Semiconductor Ecosystem," PricewaterhouseCoopers, n.d., https://www.pwc.com/us/en/library/chips-act.html.

STANFORD EXPERT CONTRIBUTOR

Dr. Herbert S. Lin
SETR Director and Editor in Chief, Research Fellow at the Hoover Institution

This publication reflects updates through December 2025

32 31 30 29 28 27 26 7 6 5 4 3 2 1

Designer: Howie Severson
Typesetter: Maureen Forys

Image credits: Linda A. Cicero/Stanford News and iStock.com/PTC-KICKCAT92 (cover); iStock.com/mofuku (p. 22); iStock.com/wacomka (p. 38); iStock.com/FeelPic (p. 56); iStock.com/JONGHO SHIN (p. 70); iStock.com/Chartchai San-saneeyashewin (p. 88); iStock.com/ArtemisDiana (p. 102); iStock.com/PhonlamaiPhoto (p. 116); iStock.com/imaginima (p. 142); iStock.com/Floriana (p. 156); iStock.com/dima_zel (p. 170); Tim Griffith (p. 225)