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A Report on Ten Key Technologies and Their Policy Implications

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BIOTECHNOLOGY AND SYNTHETIC BIOLOGY

KEY TAKEAWAYS

- Biotechnology is emerging as a general-purpose technology by which anything bioengineers learn to encode in DNA can be grown whenever and wherever needed—essentially enabling the production of a wide range of products through biological processes across multiple sectors.
- The United States is still not executing well on strategies for emerging biotechnology and has relied too heavily on private-sector investment to support foundational work needed to scale and sustain progress.
- Biotechnology is one of the most important areas of technological competition between the United States and China, and China is now leveraging two decades of strategic investment to secure global leadership. Absent swift and ambitious actions, the United States risks biotechnological surprise and a loss of biotechnology sovereignty.

Overview

Biotechnology uses living systems to make products or solve problems. First-generation biotechnology arose over millennia by domesticating and breeding plants and animals[1] for agriculture, food production, companionship, and other purposes.[2] Second-generation biotechnology was launched a half century ago with the invention of recombinant DNA,[3] and it has progressed via techniques including polymerase chain reaction, high-throughput DNA sequencing, and CRISPR gene editing.[4] (DNA is the physical material that encodes biological functions in living systems and is described in more detail later in the chapter.) Both breeding and editing approaches continue to advance, creating ever better tools for sculpting[5] and editing[6] living systems.

Biotechnology products and services are already widely deployed. A 2020 National Academies of Sciences, Engineering, and Medicine report valued the US bioeconomy at around 5 percent of GDP, or

more than $950 billion annually.[7] Most applications are in agriculture, medicines, and industrial materials.[8] A 2020 McKinsey & Company report noted that hundreds of biotechnology projects were under development that could add $2 to $4 trillion to the economy.[9] McKinsey's projected doubling of bioeconomic impacts every seven years or so would match biotechnology's economic track record.[10] Its report concluded that, ultimately, biomanufacturing could account for around 60 percent of the global economy's physical inputs.[11] Lowering the cost of biomanufacturing will be essential to realizing such a future.[12]

Synthetic biology continues to emerge as a third wave driving biotechnology, complementing breeding and DNA editing. Synthesis involves putting things together. Synthetic biology explores and adapts concepts from other engineering fields to get better at composing living systems at the molecular, cellular, tissue, and consortia scales. (Consortia refer to biological organization at the level of communities or groups of interacting organisms—typically microbial communities—that function together with division of labor, cooperation, and emergent properties beyond what single cells or tissues can achieve.)

As our ability to compose biology improves, new and more natural modes of biotechnology become possible. For example, leaves on trees do not arrive from factories or central facilities; rather, they grow on trees themselves. Next-generation biotechnology products that operate on a distributed and in situ basis are being explored. For example, a Spanish and British team recently bioengineered plants that can emit light of different colors depending on whether certain viruses are present in the environment around them.[13]

The history of information technology helps in thinking about the emergence of biotechnology. Fifty years ago, computers were mostly industrial, disconnected, and centralized.[14] The emergence of personal computers, packet-switching networks,[15] and programming languages made computing accessible and fun[16] and changed how computer science developed.[17] Biotechnology is poised to experience the same transformation within the next two decades—networked biotechnologies could enable distributed manufacturing resilience, personalized and pervasive biotechnology products, and tools for individual citizens to engage and participate in biotechnology activities.[18]

Key Developments

Analyzing and Understanding Biology with Computing

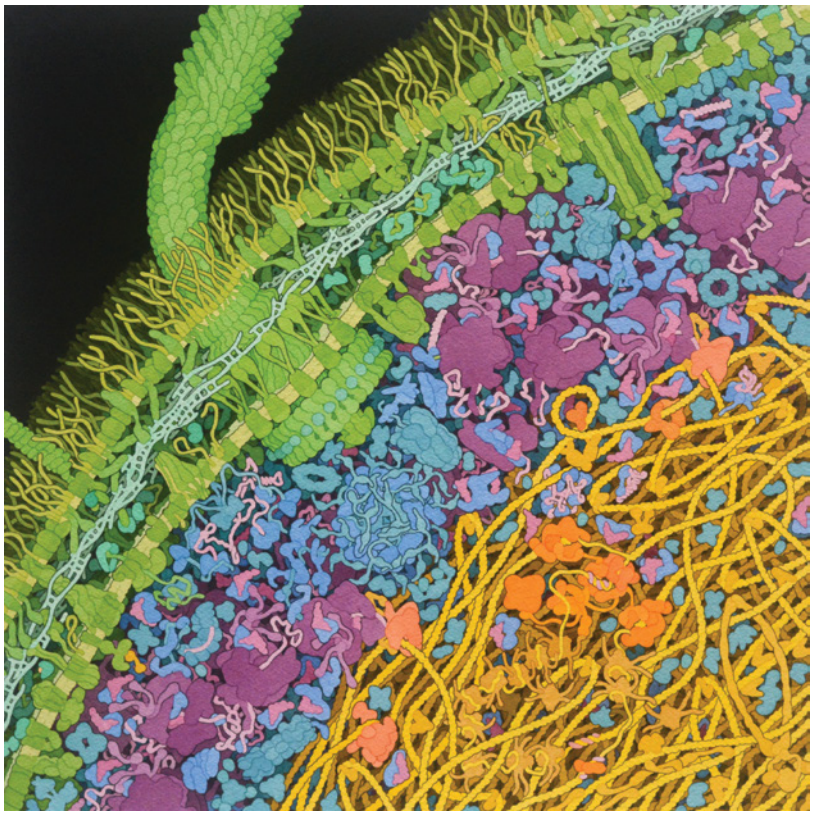
Proteins are molecules that comprise living cells. The shapes of proteins help set their roles and functions. In the 2023 edition of the *Stanford Emerging Technology Review* (*SETR*), we noted how researchers had developed artificial intelligence (AI) methods to estimate the shapes of natural proteins,[19] an accomplishment since recognized with the 2024 Nobel Prize in Chemistry.[20]

Today, AI methods accelerate research by enabling anyone with a computer to estimate the expected shapes of proteins. Researchers can quickly explore what proteins might do without having to run costly real-world experiments. Challenges remain, however. For example, it is still hard to estimate the shapes of proteins that sit within membranes and how certain proteins may change their shape.

Creating AI tools for estimating protein shapes was dependent on decades of laborious experiments by researchers; the actual shapes of enough proteins were needed to train the underlying AI models, and generating these took time. Significant additional data may be needed to develop AI models for understanding protein dynamics, drug-protein interactions, and other life-essential functions.

Cells are the fundamental unit of all living organisms (see figure 2.1). The complexity of cells has long

FIGURE 2.1 Image of a cross section of an *E. coli* cell



Source: David S. Goodsell, RCSB Protein Data Bank, doi: 10.2210/rcsb_pdb/goodsell-gallery-028

motivated researchers to develop computational tools to help make sense of things. There are not yet AI foundation models (described in chapter 1, on artificial intelligence) for representing cells in the same way that there are for representing proteins. Efforts to create "virtual cells" are taking shape, but established measurement methods and computational approaches may be insufficient.[21]

Another emerging approach is to repurpose mathematics used for describing the behavior of materials like toothpaste and ketchup. Such materials, known as "colloidal systems," are mixtures in which particles of one substance are evenly distributed throughout another in a manner similar to how molecules dynamically organize themselves within cells.[22] Recent work that has adapted such mathematical methods to study cells has shown they are capable of representing emergent behaviors that occur at the molecular-to-cellular scale.[23] Combining colloidal models, which model how molecules actually behave within cells, with AI methods is likely the best path toward achieving virtual cells.

Generating and Designing Biology with Computing

Models and software can be further developed to generate novel designs. For example, Chai-2 is an AI model that can design entirely new antibody-based

drugs from scratch. (Antibodies are proteins that bind specific target molecules.) In July 2025, Chai-2 achieved a 16 percent success rate in designing antibodies from scratch.[24] That means that 16 percent of the candidates it generates actually result in an effective antibody. Although this percentage may sound low, it compares favorably with traditional experimental lab-based methods that involve screening thousands or millions of candidates with hit rates below 1 percent; it is about one hundred times better than other computational approaches. Chai-2's effectiveness can speed up drug discovery from months or years to weeks. If generalizable, such tools might allow certain medicines to be created faster and more precisely.

Another exciting development is generative biology and genome foundation models, which were introduced in the 2025 edition of *SETR*. Since then, tools like Evo 2 have been released. Evo 2 is described as a "genomic foundation model capable of generalist prediction and design tasks across DNA, RNA, and proteins."[25] A genome foundation model is akin to a large language model trained on natural DNA sequences. When appropriately prompted, these models generate novel DNA sequences. Evo 2 is now capable of generating genomes of viruses, some of which are viable when built and tested in the laboratory.[26]

This capability enables scientists to study viral functions, evolution, and mutations systematically, thereby accelerating discoveries in virology and disease mechanisms. It also facilitates the design of synthetic viruses for beneficial uses like gene therapy, vaccines, and viral delivery systems. Compared to working with natural viruses, it also enables safer, more targeted experimentation.

One bottleneck in generative biology is the limited capacity to interpret or test what a model generates or helps design. No one can yet read entirely novel strings of nucleotides or amino acids and perfectly evaluate the biological function(s) encoded in them. Researchers need faster, better, and larger-scale testing platforms to empirically test how well AI-generated biology actually works.

Distributed Biomanufacturing

The significance of distributed biomanufacturing lies in its flexibility, both in location and timing. For example, because a fermentation process can be established wherever there is access to sugar and electricity, a production site can be set up almost anywhere. The same is true for biomanufacturing processes fed with wood, methane, petroleum, or carbon dioxide (CO_2).

Once established, a biomanufacturing process can respond swiftly to sudden demands, such as those that arise during a pandemic, amid changes in trade policy, or in the case of a war. Such agility can enhance efficiency and revolutionize manufacturing.

One real-world example is the synthetic biology company Antheia, which in early 2024 reported validation of a fermentation-based process for brewing thebaine, a key starting material used in treating opioid overdoses with Narcan.[27] It brewed 116,000-liter batches of bioengineered yeast, with each batch making broth containing a metric ton of thebaine—roughly enough for 100 million Narcan doses.[28] The company's demonstration highlights the potential for on-demand production of critical pharmaceuticals, potentially revolutionizing drug supply chains and improving access to essential medicines.

In 2022, Chinese researchers noted more generally how synthetic biology allows the rewiring of biological systems to support portable, on-site, and on-demand manufacturing of biomolecules.[29] In 2024, Stanford researchers reported on-demand bioproduction of sensors enabling point-of-care health monitoring and detection of environmental hazards aboard the International Space Station.[30] They had already realized many similar demonstrations of distributed biomanufacturing on Earth, ranging from

biotechnology education kits to the production of conjugate vaccines.[31]

Such examples demonstrate how biotechnology can be used to make valuable products and services locally. What's happening is a sort of molecular gardening: The energy and material inputs needed to make the biotechnology products are supplied locally, but the process differs from conventional gardening in that bioengineers are programming the genetic instructions for what the biology should make. To fully unlock the power of distributed biomanufacturing, it must also become possible to make the physical DNA encoding genetic programs locally.

Distributed DNA Reading and Writing

DNA is often represented abstractly by its four constituent bases (A, C, T, and G). Unique orderings of these bases encode different biomolecules, which in turn underlie different cellular behaviors and functions.

DNA sequencing (reading of DNA) and synthesis (writing of DNA) are two foundational technologies underlying synthetic biology.[32] Sequencers are machines that determine the precise order of bases in a DNA molecule, effectively converting genetic information from a physical to digital format. Synthesizers generate user-specified digital sequences of A's, C's, T's, and G's, creating physical genetic material from scratch that encodes user-specified sequences, effectively transforming bits into atoms.

If DNA reading and writing tools could themselves be distributed, anyone with an internet connection could upload and download application-specific DNA programs that direct distributed biomanufacturing processes powered by locally available energy and supplied by locally available materials.

In the 1990s, public funding for sequencing the human genome jump-started advances in DNA-sequencing tools by creating significant demand for reading DNA.[33] Private capital and entrepreneurs quickly responded.[34] The Human Genome Project favored development of DNA sequencers that could read billions of bases of DNA as cheaply as possible, resulting in large-format DNA sequencers that were organized in centralized DNA-sequencing factories.[35]

A complementary approach to DNA sequencing has since matured; it allows for individual DNA molecules to be sequenced via tiny pores, or nanopores.[36] UK-based Oxford Nanopore Technologies now offers small DNA sequencers that can be plugged into any computer with a USB port, allowing DNA sequencing to become a distributed technology (figure 2.2).[37]

The market for DNA synthesis has developed slowly over the past forty-five years.[38] Today, most DNA synthesis is carried out via centralized factories.[39] Customers order DNA online and receive materials via express shipping—and it can take days to weeks for the DNA factories to make the DNA molecules. Improvements in commercially available gene-length DNA synthesis services have been modest over the past decade,[40] and in Western countries the services are dependent on private capital.[41]

In June 2025, the United Kingdom's Wellcome Trust launched a Synthetic Human Genome Project via a £10 million seed initiative. The bold goal is to begin to develop tools and infrastructure needed to build synthetic human chromosomes,[42] something that would require significant advances in DNA, gene, and genome-construction technology.

A new generation of companies is also pursuing novel approaches to building DNA—most notably enzymatic DNA synthesis, which uses enzymes and simpler chemical inputs to build DNA.[43] For example, Ansa Biotechnologies is now producing DNA constructs up to 50 kilobases,[44] long enough to construct complete genes, multiple genes, or large genetic elements. This can enable more complex synthetic biology projects, genetic engineering, or even the creation of parts of small viral or bacterial genomes. Enzymatic approaches are compatible with hardware and reagent formats that could potentially enable fast, reliable, and distributed

FIGURE 2.2 Portable DNA sequencers enable biotechnology to become more distributed

Source: Oxford Nanopore Technologies, 2024

DNA synthesis. Significant and sustained investments will be required to make distributed DNA synthesis practical, secure, and accessible.

As another example, researchers in Shanghai have developed a bottom-up DNA synthesis method using DNA origami frameworks—tiny, precisely folded DNA structures—that act like miniature workstations to anchor DNA-writing enzymes at specific positions. Their approach allows ultra-high-density writing of over 500 billion DNA strands per square centimeter, a 10,000-fold improvement over current technologies.[45] If this approach is successfully commercialized, DNA might be written fast enough to support gigabyte-per-second data storage.

Pervasive and Embedded Biotechnologies

The assumption underlying most modern biotechnology products is that they will be carefully contained in steel tanks or used far away from urban populations. However, recent developments in consumer biotechnology products suggest another future. US-based Light Bio, for example, now sells petunia plants bioengineered to emit light (figure 2.3).[46] Light Bio's offering represents an early successful launch of a live consumer biologic, enabling anyone in the United States to source and keep a bioengineered organism for personal use.

In 2024, UK-based Norfolk Plant Sciences first made available to US consumers seeds for its purple tomato, a kind of tomato bioengineered to produce high levels of antioxidants thought to help prevent cancer (see figure 2.4).[47] Stanford faculty bought seeds, and soon bioengineered tomatoes were growing in gardens across campus. Indeed, these tomatoes are available for consumer purchase in a number of grocery stores in the American southeast.[48]

FIGURE 2.3 Light Bio's petunias are bioengineered to emit light

Source: Light Bio Inc.

Another US-based company, ZBiotics, has launched fiber-focused innovations. ZBiotics' Sugar-to-Fiber probiotic drink mix is a genetically engineered microbe that turns dietary sugar into fiber during digestion.[49] This development is emblematic of a next generation of probiotics: They not only supplement the gut microbiome but reshape how the body interacts with food.

An additional category of pervasive and potentially consumer-facing biotechnology involves bioengineering bacteria that live on skin. For example, in 2023, Stanford researchers pioneered the bioengineering of skin microbes to combat skin cancer.[50] Researchers have since expanded such work to enable the eliciting of antigen-specific T cells, which target and eliminate cells infected with viruses and bacteria; these cells also play a role in providing long-term immunological memory.[51] The researchers have even identified specific odorants produced by human-skin microbes whose production could be modulated to reduce mosquito bites.[52]

Meanwhile, CAR-T cell therapy is a new treatment that helps the immune system fight diseases. It was first used for blood cancers but is now being tested for autoimmune diseases and chronic infections.[53] Usually, a patient's own immune cells are taken,

FIGURE 2.4 Norfolk Plant Sciences has bioengineered a more nutritious purple tomato

Source: Norfolk Plant Sciences

changed in a lab to better attack disease, then put back into the body. Researchers are investigating CAR-T cells made from healthy donors, creating off-the-shelf treatments made in advance.[54] These innovations suggest a future where personalized immunotherapies become common, affordable, and widely used medical tools.

Twenty-first-century biotechnologies are increasingly showing up in our homes, on our skin, and in our diets, entering everyday life through familiar channels. These breakthroughs are early indicators of a future in which biology becomes as ubiquitous and integrated in society as electricity or the internet. As noted in a recent hearing of the US-China Economic and Security Review Commission,[55] whichever nation embraces this shift most fully—by "falling in love with biotechnology" not just as science but as part of daily life—will better shape the rules, reap the economic rewards, and lead the next era of bioinnovation.

Over the Horizon

Routinization of Cellular-Scale Engineering

There is no natural cell on Earth that is fully understood. Even well-studied organisms like *E. coli* have genes encoding unknown functions. The simplest and most intensely studied microbes still require more than seventy genes whose functions no researcher understands.[56]

Our ignorance means that biotechnology workflows remain Edisonian at the cellular scale, dependent on tinkering and testing. Bioengineering students are taught "design, build, test, learn"[57] as dogma, with testing requiring many experiments to understand basic phenomenology. Biotechnology projects thus require expert researchers and expensive laboratories while also encountering uncertain budgets and timelines.

Another approach is to build cells starting from only chemically defined molecules. Work based on this approach has rapidly advanced over the past decade, and researchers anticipate soon reporting the first artificial synthetic cells capable of growth, division, and evolution—representing a Sputnik-like milestone for biotechnology. Realizing this potential depends on routinizing bioengineering workflows at the cellular scale to enable "design, build, work" cycles. Such workflows would allow bioengineers to perform relatively minimal empirical validation, focusing primarily on analysis-driven construction of biological artifacts—a hallmark of the engineering rigor found in all modern technologies and essential for future scalable bioengineering.[58]

Constructing simple life from scratch will enable the transcendence of constraints on Earth's lifeforms[59]—organisms limited by lineage and requirements of reproduction and evolvability. A next level of biotechnologies will be unlocked, providing a perch from which to access everything biology can become. More practically, gaining the capacity to make the engineering of cellular-scale systems

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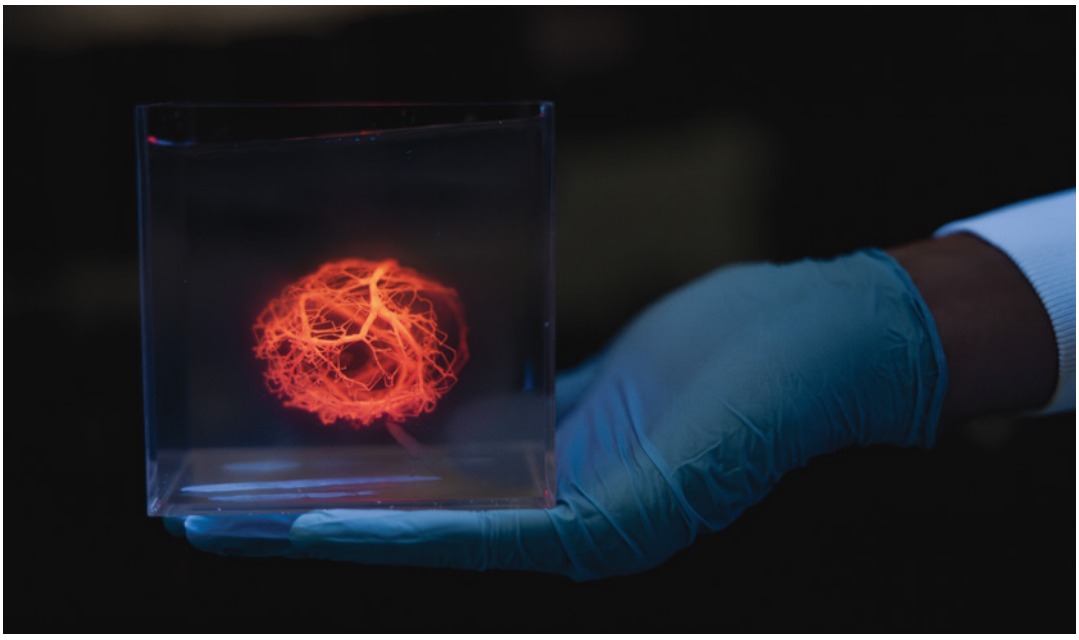
FIGURE 2.5 A model of a vascular tree printed using a 3-D bioprinter



Source: Andrew Brodhead, *Stanford Report*

routine will enable the development and deployment of biotechnologies on a much more reliable basis.

Printing Tissues on Demand

Tissue printing uses living cells as inks to construct tissue-like structures. Early methods relied on sparse inks around one hundred times less dense than natural tissue. Recent breakthroughs are enabling printing with about 200 million cells per milliliter,[60] a density approaching that found in live organs.

At Stanford, Mark A. Skylar-Scott and his team have developed a method called SWIFT (sacrificial writing into functional tissue) that helps create living heart tissue in the lab. Starting with hundreds of thousands of tiny clusters of special stem cells and mixing them into a soft paste, they "print" tiny channels inside this mixture, similar to making blood vessels. This allows oxygen and nutrients to flow through the tissue and helps the cells survive, join together, and even start beating like a real heart (figure 2.5).

Making enough cells remains a key challenge. Skylar-Scott's team can generate billions of heart-specific cells every two weeks via automated bioreactors.[61] Further increases in cell production combined with organ-scale design will be needed to print implant-ready tissues.[62]

Such developments reflect a broader shift in the field of tissue engineering and printing—from simple cell sheets to dense, vascularized, and physiologically active tissue systems. Once confined to small-scale tissue patches or skin grafts, the field is now generating, among other things, tissue that supports perfusion, which covers flowing blood or fluid through blood vessels to oxygenate and feed tissues and organs; functional integration (i.e., an integration of multiple components in a tissue or other biological construct that performs desired biological functions

in a reliable and functional manner); and long-term viability of engineered tissues. The dreams of building whole-tissue or full-organ fabrication are shifting from speculation to matters of engineering rigor, scale, investment, and translation.

Electrobiosynthesis

Carbon is central to life. Currently, photosynthesis captures CO_2 from the atmosphere to produce organic carbon molecules. Recent thinking, however, suggests that electricity could be used to fix carbon directly from the air to create organic molecules that could be fed to microbes—a process that may become known as electrobiosynthesis, or, more simply, as "eBio." Capturing carbon in this way could be an order of magnitude more efficient from a land-use perspective than traditional agriculture.[63]

The idea is to engineer a parallel carbon cycle that starts with air and electricity, perhaps generated via solar panels, to create organic molecules that power bioproduction processes. For example, in 2024, Stanford researchers reported the creation of a system that combines electrochemistry with biological processes to transform simple carbon compounds into a key organic molecule called acetyl-CoA (acetyl coenzyme A), which is present in all living things and acts as a building block for other molecules within cells.[64]

Although eBio is a very immature technology, its potential significance and impacts are hard to overstate. For example, surplus power from large-scale renewable energy generation might directly produce biomolecules such as proteins and cellulose without requiring massive conventional battery banks to store energy that cannot be used immediately. The development of eBio could also enable bioproduction in places where soils are poor, water is scarce, or climate and weather are too uncertain.

Ultimately, eBio could increase how much humanity can make in partnership with biology. We would be constrained only by how much energy we can generate for such purposes. This approach could significantly reduce the land and water requirements for biomass production, potentially alleviating pressure on agricultural resources and offering a more sustainable path for biomanufacturing.

Biology as a General-Purpose Technology

Biotechnology is now used to make medicines, foods, and a relatively narrow range of materials (e.g., sustainable carpet fibers). However, anything whose biosynthesis engineers can learn to encode in DNA could be grown using biology. Examples from nature highlight the potential here: Some bacteria naturally grow arrays of tiny magnets,[65] while select sea sponges grow glass filaments like fiber-optic cables.[66] These bio-made magnets and filaments form under ambient conditions through naturally sustainable processes and can be more robust than conventional alternatives. Such examples fuel calls for biology to be recognized as a general-purpose technology that, with appropriate vision and leadership, could become the foundation of a much more resilient manufacturing base.[67]

As one example, in 2018 the Semiconductor Research Corporation (SRC) offered an ambitious twenty-year synthetic biology road map toward growing computers.[68] SRC's first proposed step was to develop DNA for archival data storage.[69] In 2024 the Hoover Library & Archives partnered with Twist Bioscience to encode a digital copy of the telegram from President Hoover founding his namesake institution within synthetic DNA contained in a tiny ampule (see figure 2.6). Made in this way, the DNA serves as a data storage medium whose digital contents must be recovered via DNA sequencing. In April 2025, the Library of Congress requested proposals to store 1 terabyte of data in synthetic DNA. The intention is to provide "both a functional and artistic display" of some of the nation's digital treasures in celebration "of the 250th anniversary of the signing of the Declaration of Independence."[70]

Many other things must be made real to ever grow computers. Scattered progress is happening: In 2024 researchers in California reported using a synthetic

FIGURE 2.6 DNA is used as a storage medium for a digital copy of Herbert Hoover's telegram founding his namesake institution

monolayer of DNA origami to assemble and study solid-state spin qubits for quantum sensing applications. (Qubits and quantum sensing are described further in chapter 7, on quantum technologies.)[71]

Another example is the 2011 US Navy program Application of Synthetic Biological Techniques for Energetic Materials.[72] This program explored the ability to brew propellants and explosives—an ability that could enable any nation to create more resilient supply chains for key military materials. For example, a distributed and resilient biomanufacturing network could help NATO members meet their Article 3 obligations related to supply chain resilience.[73]

Unlocking biology as a general-purpose technology by learning to grow computers, energetics, and many other things might require $100 billion in well-managed foundational research over a twenty-year period. As yet, no such coordinated effort is underway.

Policy Issues

Getting Private and Public Investments Right

Many first-generation synthetic biology companies continue to struggle.[74] Billions of dollars of private capital have been lost in biotechnology investments made in the United States alone over the past two decades. One perspective is that these early big bets were simply too early.[75] The hope is that small and scrappy efforts will eventually find their way to success. However, an immediate issue is that many sources of private capital that could support next-generation biotechnology companies are now shut off because those prior bets were unsuccessful; this adds sector-specific headwinds to the general challenges that face young, innovative businesses.

Another perspective is that America has relied too heavily on the private sector to invent, advance, and deploy emerging biotechnologies.[76] Because many private investors expect foundational advances and platforms to quickly generate and sustain revenue growth in order to justify increased valuations and further funding, young biotechnology companies go to market too early and experience a pattern of repeated failures. A June 2025 congressional hearing explored breaking this cycle via smart and sustained public investments in foundational bioengineering research, including tools for measuring, modeling, and making biology and public-benefit research platforms.[77]

Safety and Security Concerns

New organisms can raise concerns about how they might interact with natural or human environments. Bioengineered organisms might disrupt local ecosystems. Malicious actors could create organisms harmful to people or environments.[78]

A specific recent concern is the potential construction of mirror life and mirror microorganisms. Mirror life—entirely hypothetical today—is made of biological molecules that are mirror images of those found in natural life on Earth. For example, all known DNA is left-handed, referring to the spiral shape of DNA. Mirror DNA, which would be found in mirror cells, would be right-handed. All biological molecules found on Earth—DNA, sugars, fats, and proteins—have handedness, and mirror versions of these molecules would have the opposite handedness.

Mirror life is the natural end point of research on mirror-image biology, which has potential value in a variety of applications. For example, mirror-image molecules might help therapeutic drugs resist undesirable natural enzymatic degradation in the human body. Mirror cells could be the most economical way to produce such molecules.

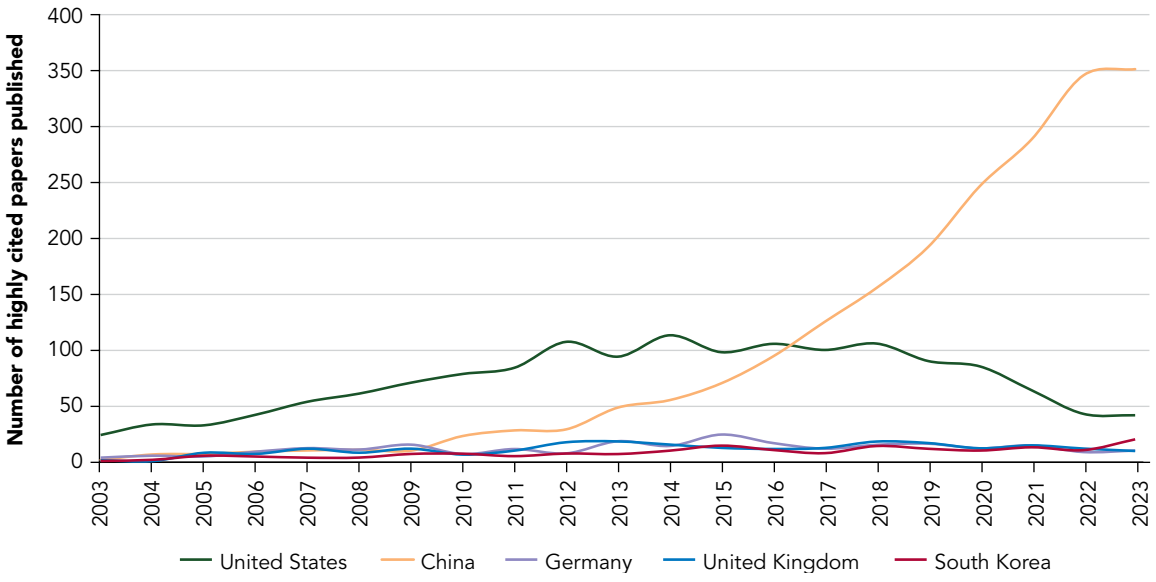
However, if they escaped into the environment, such organisms might not be readily recognized by the immune systems of plants and animals, including humans. The increasing risk of someone making mirror microbes has resulted in calls for outright bans and prohibitions on such work.[79]

Reflecting such types of concern, experts in the life sciences convened in February 2025 for the Spirit of Asilomar and the Future of Biotechnology summit. It took place on the fiftieth anniversary of the original Asilomar conference, which had convened to address the potential biohazards of recombinant DNA. The 1975 conference ultimately resulted in the establishment of voluntary guidelines and safety principles for the responsible conduct of genetic engineering research and set an important precedent for self-regulation in biotechnology.

The 2025 Spirit of Asilomar was organized around discussions of several themes,[80] including pathogens research and biological weapons, AI and biotechnology, synthetic cells, biotechnologies beyond conventional containment, and the framing of biotechnology's futures. The conference resulted in the publication of twenty-seven entreaties—public recommendations and calls for dialogue spanning these themes.[81] The 2025 conference organizers hope that these entreaties will constitute an important point of departure for proactive, forward-looking governance that addresses both known risks and emerging challenges at the intersection of synthetic biology, AI, and global biosecurity.

Additionally, concerns about biosafety and biosecurity have stimulated interest in a variety of control measures to ensure appropriate use of biotechnology and strengthen the governance of pathogen-related research.[82] For example, a rapid increase in the deployment of BSL-3 and BSL-4 laboratories (biological laboratories with the highest biosafety levels and thus the most stringent safety and security measures) reflects heightened attention to biosafety and biosecurity needs as more researchers work with higher-risk pathogens and synthetic biology tools.

FIGURE 2.7 China is outpacing the United States in publishing highly cited research papers on synthetic biology



Source: Adapted from Australian Strategic Policy Institute, Critical Technology Tracker, based on "Appendix 2: Detailed Methodology," in Jennifer Wong-Leung, Stephan Robin, and Danielle Cave, ASPI's Two-Decade Critical Technology Tracker, August 2024

Ethical Considerations

Different religious traditions may have different stances toward life and whether the engineering of new life-forms violates any of their basic precepts. In the words of a report published by the Woodrow Wilson International Center for Scholars, such concerns involve "the possibility of harm to deeply held (if sometimes hard to articulate) views about what is right or good, including . . . the appropriate relationship of humans to themselves and the natural world."[83] Just because something might or can be done does not mean that it should be done.

As Drew Endy (the SETR faculty member for biotechnology) and Laurie Zoloth note, "The narrative of creation of the human is the central narrative for many religious communities. To create a human genome from scratch would be an enormous moral gesture whose consequences should not be framed initially on the advice of lawyers and regulators alone."[84]

Global Competition

The United States and other nations continue to develop, advance, and refine strategies for biotechnology, biomanufacturing innovation, biosecurity, and the overall bioeconomy. For example, the United States' Congressional National Security Commission on Emerging Biotechnology has now published its final report,[85] calling for bold investments in emerging biotechnology domestically.

From a competition perspective, many have been sounding the alarm that China risks outpacing the United States and Europe in established and emerging biotechnology, from research to innovation to commercialization and full-scale manufacturing.[86] For example, in 2023 researchers in China published nearly 350 papers that ranked among the top 10 percent most-cited papers on synthetic biology. This is compared to 41 such papers in the United States (see figure 2.7). As another example, licensing

of novel drugs has seen a dramatic shift, with China-based firms reporting an almost twentyfold increase in licensing deals over the past decade.[87]

If the United States and Europe fail to match China's all-of-nation support for biotechnology, then neither will maintain biotechnology leadership or sovereignty going forward. Absent dramatic action, such failure seems a most likely outcome; plaintive warnings or calls for action from researchers in the West simply help spur greater investments from Beijing.

NOTES

1. Jared Diamond, "Evolution, Consequences, and Future of Plant and Animal Domestication," *Nature* 418 (August 2020): 700–707, https://doi.org/10.1038/nature01019.

2. Freeman Dyson, "Our Biotech Future," *New York Review of Books* 54, no. 12 (July 2007): 4–7, https://www.nybooks.com/articles/2007/07/19/our-biotech-future/.

3. Tim Beardsley, "Biotechnology: Cohen-Boyer Patent Finally Confirmed," *Nature* 311, no. 5981 (September 1984): 3, https://doi.org/10.1038/311003a0.

4. Irina Gostimskaya, "CRISPR-Cas9: A History of Its Discovery and Ethical Considerations of Its Use in Genome Editing," *Biochemistry* (Moscow) 87, no. 8 (August 2022): 777–78, https://doi.org/10.1134/S0006297922080090. CRISPR is an acronym for clustered regularly interspaced short palindromic repeats.

5. Frances H. Arnold, "Innovation by Evolution: Bringing New Chemistry to Life," December 8, 2018, Stockholm University, Sweden, PDF, https://www.nobelprize.org/prizes/chemistry/2018/arnold/lecture/.

6. "Genetic Scissors: A Tool for Rewriting the Code of Life," news release, the Nobel Prize, October 7, 2020, https://www.nobelprize.org/prizes/chemistry/2020/press-release/.

7. National Academies of Sciences, Engineering, and Medicine, "Safeguarding the Bioeconomy" (National Academies Press, 2020), 73, https://doi.org/10.17226/25525.

8. Planetary Technologies, "Bioeconomy Dashboard," last modified 2023, https://www.planetarytech.earth/bioeconomy-dashboard-1.

9. Michael Chui, Matthias Evers, James Manyika, Alice Zheng, and Travers Nisbet, "The Bio Revolution: Innovations Transforming Economies, Societies, and Our Lives," McKinsey & Company, May 13, 2020, https://www.mckinsey.com/industries/life-sciences/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives.

10. Robert Carlson, "Estimating the Biotech Sector's Contribution to the US Economy," *Nature Biotechnology* 34, no. 3 (March 2016): 247–55, https://doi.org/10.1038/nbt.3491.

11. Chui, Evers, Manyika, Zheng, and Nisbet, "The Bio Revolution."

12. Jennifer Hennigan, Phillip Wagner, Chris Burk, et al., "A Technoeconomic Evaluation of the Potential of Industrial Biotechnology for the Competitive Production of Commodity and Bulk Chemicals," preprint, ChemRxiv, November 16, 2020, https://doi.org/10.26434/chemrxiv.13238996.v1.

13. Camilo Calvache, Marta Rodriguez-Rodriguez, Victor Vazquez-Vilriales, et al., "Bioluminescent Sentinel Plants Enable Autonomous Diagnostics of Viral Infections," preprint, bioRxiv, January 1, 2025, 2025.08.05.668616, https://doi.org/10.1101/2025.08.05.668616.

14. "IBM Mainframe," Wikipedia, last modified July 20, 2024, https://en.wikipedia.org/wiki/IBM_mainframe.

15. Vinton G. Cerf and Robert E. Kahn, "A Protocol for Packet Network Intercommunication," *IEEE Transactions on Communications* 22, no. 5 (May 1974): 637–48, https://doi.org/10.1109/TCOM.1974.1092259.

16. *Whole Earth Epilog* (Penguin Books, 1974), https://archive.org/details/wholeearthepilog00unse.

17. "History of Personal Computers," Wikipedia, last modified August 19, 2024, https://en.wikipedia.org/wiki/History_of_personal_computers.

18. Callie R. Chappell, Ana Paulina Quiroz, David Sun Kong, and Drew Endy, "Creating a Popular Foundation for the Bio-Age," *Issues in Science and Technology* 41, no. 4 (Summer 2025): 60–63, https://doi.org/10.58875/LCHC2652.

19. Ewen Callaway, "'The Entire Protein Universe': AI Predicts Shape of Nearly Every Known Protein," *Nature*, July 29, 2023, https://www.nature.com/articles/d41586-022-02083-2.

20. "Summary," the Nobel Prize in Chemistry 2024, the Nobel Prize, October 12, 2024, https://www.nobelprize.org/prizes/chemistry/2024/summary/.

21. Elliot Hershberg, "What Are Virtual Cells?," The Century of Biology, June 29, 2025, https://centuryofbio.com/p/virtual-cell.

22. Akshay J. Maheshwari, Alp M. Sunol, Emma Gonzalez, Drew Endy, and Roseanna N. Zia, "Colloidal Hydrodynamics of Biological Cells: A Frontier Spanning Two Fields," *Physical Review Fluids* 4, no. 11 (2019): 110506, https://doi.org/10.1103/PhysRevFluids.4.110506.

23. Akshay J. Maheshwari, Jonathan Calles, Sean K. Waterton, and Drew Endy, "Engineering tRNA Abundances for Synthetic Cellular Systems," *Nature Communications* 14, no. 1 (2023): 4594, https://doi.org/10.1038/s41467-023-40199-9; Akshay J. Maheshwari, Alp M. Sunol, Emma Gonzalez, Drew Endy, and Roseanna N. Zia, "Colloidal Physics Modeling Reveals How Per-Ribosome Productivity Increases with Growth Rate in Escherichia Coli," *mBio* 14, no. 1 (2022): e02865–22, https://doi.org/10.1128/mbio.02865-22.

24. Chai Discovery Team et al., "Zero-Shot Antibody Design in a 24-Well Plate," preprint, bioRxiv, July 6, 2025, https://doi.org/10.1101/2025.07.05.663018.

25. "Evo 2: DNA Foundation Model," Arc Institute, 2024, https://arcinstitute.org/tools/evo; Eric Nguyen, Michael Poli, Matthew G. Durrant, et al., "Sequence Modeling and Design from Molecular to Genome Scale with Evo," preprint, bioRxiv, March 6, 2024, https://doi.org/10.1101/2024.02.27.582234.

26. Samuel H. King, Claudia L. Driscoll, David B. Li, et al., "Generative Design of Novel Bacteriophages with Genome Language Models," preprint, bioRxiv, January 1, 2025, 2025.09.12.675911, https://doi.org/10.1101/2025.09.12.675911.

27. "Antheia Completes Successful Product Validation," Antheia, January 8, 2024, https://antheia.bio/antheia-completes-successful-product-validation/.

28. "U.S. Secretary of State Antony Blinken Visits Antheia to Discuss Biotechnology Innovation," Antheia, May 30, 2024,

https://antheia.bio/u-s-secretary-of-state-antony-j-blinken-visits-antheia-to-discuss-biotechnology-innovation/.

29. Chenwang Tang, Lin Wang, Lei Zang, Qing Wang, Dianpeng Qi, and Zhuojun Dai, "On-Demand Biomanufacturing Through Synthetic Biology Approach," *Materials Today Bio* 18, no. 100518 (February 2023), https://doi.org/10.1016/j.mtbio.2022.100518.

30. Selin Kocalar, Bess M. Miller, Ally Huang, et al., "Validation of Cell-Free Protein Synthesis Aboard the International Space Station," *ACS Synthetic Biology* 13, no. 3 (March 2024): 942–50, https://doi.org/10.1021/acssynbio.3c00733.

31. Jessica C. Stark, Thapakorn Jaroentomeechai, Tyler D. Moeller, et al., "On-Demand Biomanufacturing of Protective Conjugate Vaccines," *Science Advances* 7, no. 6 (February 2021): eabe9444, https://doi.org/10.1126/sciadv.abe9444; Jessica C. Stark, Ally Huang, Peter Q. Nguyen, et al., "BioBits™ Bright: A Fluorescent Synthetic Biology Education Kit," *Science Advances* 4, no. 8 (August 2018): eaat5107, https://doi.org/10.1126/sciadv.aat5107.

32. National Security Commission on Emerging Biotechnology, "DNA: Reading, Writing, and Editing," February 2024, https://www.biotech.senate.gov/press-releases/dna-reading-writing-and-editing/.

33. "The Human Genome Project," National Human Genome Research Institute, National Institutes of Health, last modified May 14, 2024, https://www.genome.gov/human-genome-project.

34. Kristen Philipkoski, "Celera Wins Genome Race," *Wired*, April 6, 2000, https://www.wired.com/2000/04/celera-wins-genome-race/.

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

36. Davied Deamer, Mark Akeson, and Daniel Branton, "Three Decades of Nanopore Sequencing," *Nature Biotechnology* 34 (May 2016): 518–24, https://doi.org/10.1038/nbt.3423.

37. "Company History," Oxford Nanopore Technologies, accessed September 3, 2024, https://nanoporetech.com/about/history.

38. Marvin H. Caruthers, "The Chemical Synthesis of DNA/RNA: Our Gift to Science," *Journal of Biological Chemistry* 288, no. 2 (December 2012): 1420–24, https://doi.org/10.1074/jbc.X112.442855.

39. "Integrated DNA Technologies Invests in New U.S. Synthetic Biology Manufacturing Facility," Business Wire, May 28, 2024, https://www.businesswire.com/news/home/20240528727951/en/Integrated-DNA-Technologies-Invests-in-New-U.S.-Synthetic-Biology-Manufacturing-Facility.

40. Planetary Technologies, "Bioeconomy Dashboard."

41. "Twist Bioscience Expands Gene Offering with Long Gene Fragments up to 5.0kb," Business Wire, August 8, 2024, https://www.businesswire.com/news/home/20240808863612/en/Twist-Bioscience-Expands-Gene-Offering-With-Long-Gene-Fragments-up-to-5.0kb.

42. "New Project to Pioneer the Principles of Human Genome Synthesis," Wellcome Trust, June 26, 2025, https://wellcome.org/news/new-project-pioneer-principles-human-genome-synthesis.

43. MaryAnn Labant, "Enzymatic DNA Synthesis: Shorter Waits, Longer Strands," *Genetic Engineering & Biotechnology News*, July 1, 2024, https://www.genengnews.com/topics/omics/enzymatic-dna-synthesis-shorter-waits-longer-strands.

44. "Ansa Biotechnologies Announces Successful de novo Synthesis of World's Longest Oligonucleotide at 1005 Bases," CRISPR Medicine News, March 9, 2023, https://crisprmedicinenews.com/press-release-service/card/ansa-biotechnologies-announces-successful-de-novo-synthesis-of-worlds-longest-oligonucleotide-at-10-1/.

45. Chunhong Li, Yishakejiang Saimaiti, Min Li, et al., "DNA Framework Array Enables Ultra-High Throughput DNA Synthesis," preprint, bioRxiv, May 31, 2025, https://doi.org/10.1101/2025.05.30.657018.

46. "Light Bio," Light Bio, accessed September 3, 2024, https://www.light.bio.

47. Sasa Woodruff, "Gardeners Can Now Grow a Genetically Modified Purple Tomato Made with Snapdragon DNA," NPR, February 6, 2024, https://www.npr.org/sections/health-shots/2024/02/06/1228868005/purple-tomato-gmo-gardeners.

48. "Empress Limited Edition Tomato," Norfolk Healthy Produce, accessed September 3, 2024, https://www.norfolkhealthyproduce.com.

49. "ZBiotics Sugar-to-Fiber Probiotic Drink Mix," Prepared Foods, October 12, 2024, https://www.preparedfoods.com/articles/129812-zbiotics-sugar-to-fiber-probiotic-drink-mix.

50. Hadley Leggett, "Researchers Use Skin-Colonizing Bacteria to Create a Topical Cancer Therapy in Mice," Stanford Medicine, April 12, 2023, https://med.stanford.edu/news/all-news/2023/04/cancer-bacteria.html.

51. Michael A. Fischbach, Kazuki Nagashima, Yiyin E. Chen, and Djenet Bousbaine, "Bacteria-Engineered to Elicit Antigen-Specific T Cells," US Patent 2024/0024380 A1, filed December 22, 2021, and issued January 25, 2024.

52. Iliano V. Coutinho-Abreu, Omid Jamshidi, Robyn Raban, Katayoon Atabakhsh, Joseph A. Merriman, and Omar S. Akbari, "Identification of Human Skin Microbiome Odorants that Manipulate Mosquito Landing Behavior," *Scientific Reports* 14, no. 1631 (January 2024), https://doi.org/10.1038/s41598-023-50182-5.

53. Yaojie Kong, Jingyao Li, Xueyao Zhao, et al., "CAR-T Cell Therapy: Developments, Challenges and Expanded Applications from Cancer to Autoimmunity," *Frontiers in Immunology* 15 (2024), https://doi.org/10.3389/fimmu.2024.1519671.

54. "CAR T Cells: Engineering Patients' Immune Cells to Treat Their Cancers," National Cancer Institute, February 26, 2025, https://www.cancer.gov/about-cancer/treatment/research/car-t-cells.

55. Drew Endy, "STRANGE COMPETITION. A Statement of Evidence Written in 2025," testimony presented before the US-China Economic and Security Review Commission, hearing on "Made in China 2025—Who Is Winning?," February 6, 2025.

56. John I. Glass, Chuck Merryman, Kim S. Wise, Clyde A. Hutchison III, and Hamilton O. Smith, "Minimal Cells—Real and Imagined," *Cold Spring Harbor Perspectives in Biology* 9, no. 12 (December 2017): a023861, https://doi.org/10.1101/cshperspect.a023861.

57. Shohei Kitano, Ciai Lin, Jee Loon Foo, and Matthew Wook Chang, "Synthetic Biology: Learning the Way Toward High-Precision Biological Design," *PLOS Biology* 21, no. 4 (April 2023): e3002116, https://doi.org/10.1371/journal.pbio.3002116.

58. A useful description of the contrast between "design-build-test-learn" and "design-build-work" can be found at https://centuryofbio.com/p/design-build-work.

59. Drew Endy, "Upwelling," *Original Syn*, blog, October 28, 2020, https://blog.originalsyn.bio/2020/10/upwelling.html.

60. Mark A. Skylar-Scott, Sebastien G. M. Uzel, Lucy L. Nam, et al., "Biomanufacturing of Organ-Specific Tissues with High Cellular

Density and Embedded Vascular Channels," *Science Advances* 5, no. 9 (September 6, 2019): eaaw2459, https://doi.org/10.1126/sciadv.aaw2459.

61. "Moonshot Effort Aims to Bioprint a Human Heart and Implant It in Pig," news release, Stanford News, September 23, 2023, https://news-archive.stanford.edu/press-releases/2023/09/28/moonshot-effort-eart-implant-pig.

62. Zachary A. Sexton, Dominic Rütsche, Jessica E. Herrmann, et al., "Rapid Model-Guided Design of Organ-Scale Synthetic Vasculature for Biomanufacturing," *Science* 388, no. 6752 (June 12, 2025): 1198–1204, https://doi.org/10.1126/science.adj6152.

63. Dorian Leger, "Photovoltaic-Driven Microbial Protein Production Can Use Land and Sunlight More Efficiently than Conventional Crops," *Proceedings of the National Academy of Sciences USA* 118, no. 26 (June 2021): e2015025118, https://doi.org/10.1073/pnas.2015025118; Emiliano Bellini, "Solar-Powered Large Scale Microbial Food Production," *pv Magazine*, August 3, 2021, https://www.pv-magazine.com/2021/08/03/solar-powered-large-scale-microbial-food-production.

64. Grant M. Landwehr, Bastian Vogeli, Cong Tian, et al., "A Synthetic Cell-Free Pathway for Biocatalytic Upgrading of One-Carbon Substrates," preprint, bioRxiv, August 8, 2024, https://doi.org/10.1101/2024.08.08.607227.

65. Pranami Goswami, Kuang He, Jinhua Li, Yongxin Pan, Andrew P. Roberts, and Wei Lin, "Magnetotactic Bacteria and Magnetofossils: Ecology, Evolution, and Environmental Implications," *NPJ Biofilms and Microbiomes* 8, no. 43 (June 2022), https://doi.org/10.1038/s41522-022-00304-0.

66. Sarah Graham, "Sea Sponge Inspires Better Fiber-Optic Cables," *Scientific American*, August 21, 2003, https://www.scientificamerican.com/article/sea-sponge-inspires-bette/.

67. Abigail Kukura, PJ Maykish, David Lin, et al., "National Action Plan for U.S. Leadership in Biotechnology," Special Competitive Studies Project, April 12, 2023, 1, https://www.scsp.ai/wp-content/uploads/2023/04/National-Action-Plan-for-U.S.-Leadership-in-Biotechnology.pdf.

68. "SemiSynBio Consortium and Roadmap Development," Semiconductor Research Corporation, accessed September 3, 2024, https://www.src.org/program/grc/semisynbio/semisynbio-consortium-roadmap.

69. "DNA Data Storage Alliance," DNA Data Storage Alliance, accessed September 3, 2024, https://dnastoragealliance.org.

70. "Synthetic DNA Data Storage—Library of Congress Request for Information," Sam.gov, 2025, https://sam.gov/opp/adc4a2ac1f2445de83eacfc62a8e75dd/view.

71. Zhiran Zhang, "Probing and Engineering the Environment of Near-Surface Nitrogen-Vacancy Centers in Diamond for Quantum Sensing and Simulation" (PhD diss., University of California–Santa Barbara, 2024).

72. "Synthetic Biological Techniques for Energetic Materials," Strategic Environmental Research and Development Program, Environmental Security Technology Certification Program, accessed September 3, 2024, https://serdp-estcp.mil/newsitems/details/ac878993-2005-4182-948a-f63c95668499/synthetic-biological-techniques-for-energetic-materials.

73. "Resilience in NATO," NATO Allied Command Transformation, December 15, 2023, https://www.act.nato.int/article/resilience-in-nato/.

74 ."Biotech Firm Amyris Files for Bankruptcy in US," Reuters, August 10, 2023, https://www.reuters.com/business/biotech-firm-amyris-files-bankruptcy-us-2023-08-10; Amy Feldman and Angel Au-Yeung, "The Inside Story of How SoftBank-Backed Zymergen Imploded Four Months After Its $3 Billion IPO," *Forbes*, October 13, 2021, https://www.forbes.com/sites/amyfeldman/2021/10/13/the-inside-story-of-how-softbank-backed-zymergen-imploded-four-months-after-its-3-billion-ipo.

75. Robert F. Service, "Synthetic Biology, Once Hailed as a Moneymaker, Meets Tough Times," *Science*, August 22, 2024, https://www.science.org/content/article/synthetic-biology-once-hailed-moneymaker-meets-tough-times.

76. Drew Endy, "Funding Biotechnology's Foundations to Fuel Private Sector Innovations," testimony, *Pursuing the Golden Age of Innovation: Strategic Priorities in Biotechnology*, a joint meeting of the Research and Technology and Energy Subcommittees of the Committee on Science, Space, and Technology of the US House of Representatives, June 5, 2025, https://www.hoover.org/research/joint-research-technology-and-energy-subcommittee-hearing-pursuing-golden-age-innovation-0.

77. *Pursuing the Golden Age of Innovation: Strategic Priorities in Biotechnology*, a joint meeting of the Research and Technology and Energy Subcommittees of the Committee on Science, Space, and Technology of the US House of Representatives, June 5, 2025, https://science.house.gov/2025/6/pursuing-the-golden-age-of-innovation-strategic-priorities-in-biotechnology.

78. For example, polio, horsepox, SARS-CoV-2, and the Spanish flu virus have been synthesized from scratch in laboratories. See, respectively, Jeronimo Cello, Aniko V. Paul, and Eckard Wimmer, "Chemical Synthesis of Poliovirus cDNA: Generation of Infectious Virus in the Absence of Natural Template," *Science* 297, no. 5583 (2002): 1016–18, https://www.science.org/doi/10.1126/science.1072266; Ryan S. Noyce, Seth Lederman, David H. Evans, "Construction of an Infectious Horsepox Virus Vaccine from Chemically Synthesized DNA Fragments," *PLOS ONE* 13, no. 1 (2018): e0188453, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0188453; Tran Thi Nhu Thao, Fabien Labroussaa, Nadine Ebert, et al., "Rapid Reconstruction of SARS-CoV-2 Using a Synthetic Genomics Platform," *Nature* 582 (May 2020): 561–65, https://www.nature.com/articles/s41586-020-2294-9; Terrence M. Tumpey, Christopher F. Basler, Patricia V. Aguilar, et al., "Characterization of the Reconstructed 1918 Spanish Influenza Pandemic Virus," *Science* 310, no. 5745 (2005): 77–80, https://www.science.org/doi/10.1126/science.1119392.

79. Katarzyna P. Adamala, Deepa Agashe, Yasmine Belkaid, et al., "Confronting Risks of Mirror Life," *Science* 386, no. 6728 (2024): 1351–53, https://doi.org/10.1126/science.ads9158.

80. "Summit Themes," Spirit of Asilomar, 2025, https://www.spiritofasilomar.org/program/summit-themes.

81. "The Spirit of Asilomar and the Future of Biotechnology," Rice Research Repository, 2025, https://repository.rice.edu/communities/4825def5-159e-4969-ae67-b2faf0c3b83d.

82. Jing Li et al., "Advances in Synthetic Biology and Biosafety Governance," *Frontiers in Bioengineering and Biotechnology* 9 (April 2021): 598087, https://doi.org/10.3389/fbioe.2021.598087.

83. Erik Parens, Josephine Johnston, and Jacob Moses, "Ethical Issues in Synthetic Biology: An Overview of the Debates," Woodrow Wilson International Center for Scholars, June 2009, https://www.wilsoncenter.org/sites/default/files/media/documents/publication/synbio3.pdf.

84. Drew Endy and Laurie Zoloth, "Should We Synthesize a Human Genome?," *Dspace@MIT*, May 10, 2016, https://dspace.mit.edu/handle/1721.1/102449.

85. "Home," National Security Commission on Emerging Biotechnology, accessed September 3, 2024, https://www.biotech.senate.gov.

86. Drew Endy and Mike Kuiken, "US Must Embrace a Winning Biotech Strategy," *Boston Globe*, February 21, 2025, https://www.bostonglobe.com/2025/02/21/opinion/us-china-biotechnology-innovation-manufacturing/.

87. Iris Luo, "China's Biopharma Boom in Global Drug Licensing Deals," EC Innovations, July 3, 2025, https://www.ecinnovations.com/blog/chinas-biopharma-boom-in-global-drug-licensing-deals/.

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