BIOENGINEERING

FUTURE TODAY INSTITUTE'S 2024 TECH TREND REPORT

Our 2024 edition includes more than 700 trends, which are published individually in 16 volumes and as one comprehensive report with all trends included.

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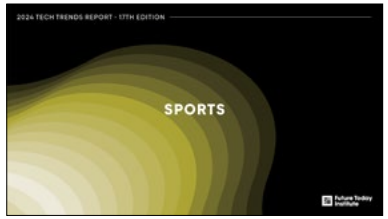

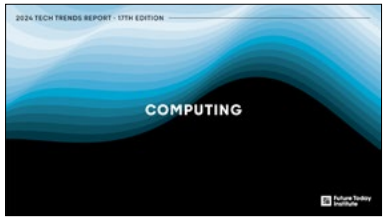

THE YEAR AHEAD: TECH SUPERCYCLE

The theme for our 2024 report is Supercycle. In economics, a "supercycle" refers to an extended period of booming demand, elevating the prices of commodities and assets to unprecedented heights. It stretches across years, even decades, and is driven by substantial and sustained structural changes in the economy.

We believe we have entered a technology supercycle. This wave of innovation is so potent and pervasive that it promises to reshape the very fabric of our existence, from the intricacies of global supply chains to the minutiae of daily habits, from the corridors of power in global politics to the unspoken norms that govern our social interactions.

Driving this seismic shift are the titans of technology and three of their inventions: artificial intelligence, biotechnology, and a burgeoning ecosystem of interconnected wearable devices for people, pets, and objects. As they converge, these three macro tech segments will redefine our relationship with everything, from our pharmacists to our animals, from banks to our own bodies. Future Today Institute's analysis shows that every technology—AR/ VR/ XR, autonomous vehicles, low Earth orbit satellites, to name a few—connects to the supercycle in some way.

The ramifications are stark and undeniable. As this tech supercycle unfurls, there will be victors and vanquished, those who seize the reins of this epochal change, and those who are swallowed whole. For business leaders, investors, and policymakers, understanding this tech supercycle is paramount.

In this 17th edition of FTI's annual Tech Trends report, we've connected the supercycle to the nearly 700 trends we've developed. Our research is presented across 16 technology and industry-specific reports that reveal the current state of play and lists of influencers to watch, along with detailed examples and recommendations designed to help executives and their teams develop their strategic positioning. The trends span evolutionary advancements in well-established technologies to groundbreaking developments at the forefront of technological and scientific exploration. You'll see emerging epicenters of innovation and risk, along with a preview into their transformative effects across various industries.

We've visually represented the tech supercycle on the report's cover, which is an undulating image reminiscent of a storm radar. Vertical and horizontal lines mark the edges of each section's cover. When all 16 section covers converge, the trends reveal a compounding effect as reverberating aftershocks influence every other area of technology and science, as well as all industries.

It's the convergence that matters. In isolation, trends offer limited foresight into the future. Instead, the interplay of these trends is what reveals long-term change. For that reason, organizations must not only remain vigilant in monitoring these evolving trends but also in cultivating strategic foresight—the ability to anticipate future changes and plan for various scenarios.

Our world is changing at an unprecedented rate, and this supercycle has only just begun.

Amy Webb
Chief Executive Officer
Future Today Institute

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TOP HEADLINES

AI breakthroughs are set to make this year a turning point for biotech, CRISPR, and synthetic biology.

01 Lab-Grown Meat Is Going Mainstream

Cultivated meat and synthetic dairy are emerging as sustainable and ethical alternatives to traditional animal products, and in 2024 production will start to scale.

02 CRISPR Will Treat Disease

US and UK regulators have approved the first CRISPR therapy, marking a significant step in gene editing's potential to cure genetic diseases.

03 Millions of New Materials Discovered

A new AI system from Google DeepMind predicted 2.2 million novel materials, signaling big changes ahead for batteries, computer chips, and more.

04 AI Transforms Biology Today; Biology Powers Computers Tomorrow

Scientists created organoid intelligence, a new biocomputing field using brain cells for AI, promising major efficiency gains over traditional computer systems.

05 We Aren't Prepared for a Cyber-Bio Attack

Cyberbiosecurity has emerged as a crucial unmet need at the intersection of AI and life sciences, with no formal oversight yet established.

STATE OF PLAY

Brace yourself for uncharted impacts. This could be a breakthrough year for biotechnology.

In the past year, AI breakthroughs have accelerated the convergence of biology, information systems, and advanced platforms, with the potential to fundamentally transform businesses and societies. While today, our focus is on generative AI, very soon that focus will shift to generative biology: Here, AI models will decipher the complexities of biology, leading to the creation of novel molecules, drugs, materials, consumables, and living organisms.

Our orientation to biology and the living world will change in the near future as CRISPR products, in the form of novel drug therapies and new foods, enter the market. Soon, we will no longer be constrained by existing materials to manufacture batteries, clothing, or buildings.

Lab-grown beef, chicken, and fish will scale, making it possible to consume meat without slaughter. Through cellular reprogramming, we could start to reverse the aging process. And we're on the brink of new fertility treatments that will challenge our ideas about parenthood.

These shifts will fundamentally alter our relationship with biology and the natural world, but we lack comprehensive policies to navigate them. While biotech promises to reshape our world, it also presents unprecedented risks, underscoring the need for preparedness and governance.

KEY EVENTS

JUNE 13, 2023

Pushing Limits of Embryo Models
Israeli, UK, and Chinese research teams advance embryo models beyond legal limits, prompting ethical debates.

NOVEMBER 29, 2023

AI Unlocks New Material Secrets
Google DeepMind's AI predicted structures of over 2 million potential new materials, potentially enhancing technologies like batteries, solar panels, and chips. Scientists could create around 400,000 of these materials in labs soon.

DECEMBER 8, 2023

FDA OKs Gene Therapy for Sickle Cell
Casgevy becomes the first approved commercial gene-editing treatment using CRISPR technology.

JANUARY 18, 2024

Universal Cancer Vaccine Trials
Cancer patients in the UK receive the first dose of a new mRNA therapy designed to help the body recognize and fight cancer cells.

FEBRUARY 6, 2024

GMO Seeds Sold Direct to Consumers
The FDA gives purple tomatoes, genetically enhanced to be more nutrient-dense, approval for home gardening.

LIKELY NEAR TERM DEVELOPMENTS

RAPID ACCELERATION

The rapid integration of artificial intelligence into bioengineering is catalyzing unprecedented innovation. The near future will see significant changes to traditional industries such as meat, dairy, textiles, and pharmaceuticals, while advancements should pave the way for sustainable solutions in carbon capture, plastics recycling, and biodiversity enhancement. Near-term breakthroughs in healthcare will lead to cataclysmic, long-term disruption. Leaders should deepen their understanding of bioengineering's vast potential and associated risks, enabling them to spearhead innovation in products and services, streamline processes, improve materials, and achieve cost efficiencies. This convergence also opens up new avenues for collaboration, allowing companies to explore untapped markets and forge strategic partnerships that can drive forward their competitive edge.

CRISPR's Emerging Economic Impact

The size of the global market for CRISPR technologies and their associated products is projected to exceed $4 billion by mid-decade. In the US alone, CRISPR could contribute $19 billion to GDP by 2032.

Life Extension Backlash

Life extension breakthroughs promise longer lives for some, yet they will strain social services, pensions, and other support systems for the elderly, challenging our preparedness for an aging population.

Supply Chain Disruption

In the next year, new materials poised to improve shipping's environmental footprint may disrupt traditional supply and cold chain operations dependent on outdated tech, posing significant threats to established companies.

GMO Misinformation

A new GMO backlash looms as public misinformation persists, with many unaware that the latest GMOs aim to boost produce and grains with enhanced nutrients, not just modify them for convenience or yield.

Regulatory Pressures

Federal Trade Commission actions spark fears of stifled innovation due to limits on scaling therapies via acquisitions, while the US Inflation Reduction Act ushers in a harsher pricing climate, impacting the biopharma industry's future reimbursement strategies for innovations.

Stark Health Divide

Biotech will revolutionize health care with novel drug therapies, yet their inaccessibility to developing economies risks creating a stark health divide, exacerbating global health inequalities.

11 MACRO SOURCES OF DISRUPTION

WHY BIOTECHNOLOGY TRENDS MATTER TO YOUR ORGANIZATION

Biotech Is a General Purpose Technology

As a modern "general purpose technology," bioengineering has the potential to influence an entire economy and alter society through political, economic, and social structures. By 2030, most people in developed economies will have used or consumed a product created with a bioengineering technology.

Biotech Will Change Your Value Network

Biotech advancements will transform the value network for businesses. Without active monitoring, disruptors may emerge, threatening established companies' capacity to create value and maintain their competitive edge for market share, investment, and talent.

Advancements Should Result in Optionality

Advancements in synthetic biology, CRISPR, AI, and engineering are opening up new opportunities across health care, pharmaceuticals, agriculture, food and beverage, beauty, chemicals, sustainability, energy, and materials production.

AI-Bio Convergence Requires New Strategy

The convergence of AI and biology will impact every business. Leaders will need a better understanding of bioengineering's potential and risks, so they can innovate products and services, develop processes, enhance materials, reduce costs, and seek out new partners and customers.

Disruption Is on Your Near-Term Horizon

Near-term disruptions in the traditional meat, dairy, textile, and pharmaceutical industries are imminent, with advancements offering new options for carbon capture, plastics recycling, and enhancing biodiversity, signaling a pivotal shift in environmental management.

Businesses Need New Policies

In response to bioengineering advances, businesses must develop policies that embody their values, ethics, and culture, such as the use of genetically enhanced ingredients, insurance coverage for novel genetic therapies, whether and how to promote genetic privacy, and more.

WHEN WILL BIOTECHNOLOGY DISRUPT YOUR ORGANIZATION?

Forecasted Time of Impact

0-4 YEARS	5-9 YEARS	10-14 YEARS	15+ YEARS
Medical Devices	CO_2 Capture Farming	Oil/Petroleum Sector	Computing
Vaccines	Ranching	Electricity	Life Extension
OTC Medications	Health Diagnostics	Aerospace	Off-Planet Exploration
Poultry Farming	Recycling	Cold Chains	
Defense	Chemicals	Living Materials	
Beauty	Fast Fashion		
Drug Development	Consumer Packaged Goods		
Textiles	Construction & Building Materials		
Luxury Fashion	Paints & Coatings		
	Data Storage		
	Grain		
	Automotive		

WHEN WILL BIOTECHNOLOGY DISRUPT YOUR ORGANIZATION?

Advancements in bioengineering will disrupt every industry, to some degree, within the next two decades. The Future Today Institute categorizes bioengineering as a "general purpose technology." Like the steam engine and internet before it, bioengineering has the potential to influence an entire economy and to alter society through political, economic, and social structures. For most industries, it's not a matter of if these trends will disrupt their futures but when.

Several factors are driving the momentum of bioengineering trends and the probable timing an industry will be disrupted:

Scaling
While the pace of innovation is fast across the spectrum of technologies, it takes time for a promising new biotech development to scale beyond the lab. Scaling requires discipline, patience, effort, and time.

Costs
Bioengineering research is still costly, though the price of components, equipment, and materials drops every year. Once a disruptor can make a product cheaper with bioengineering rather than traditional production, it will push faster into the mainstream. Advancements in technology will eventually bring down costs of production as we've seen in other fields, such as computing.

Constraints on adoption
Even if a technology is maturing, constraints on its adoption can hinder its influence in an industry. For example, a business may refuse to adopt an alternative bioengineering technology because it challenges a proven, successful strategy.

Regulations
The pace of technology advancement typically far exceeds any changes to regulation. Bioengineering is unique in that regulation exists, but products and processes are treated differently in every country. Regulatory and policy uncertainty could accelerate or stifle growth.

Media mentions
Increased awareness and enthusiasm can influence the momentum of a technology, even when there's been no real breakthrough. Media bursts related to bioengineering will drive momentum, especially if those stories are favorable and—importantly—easily understood by the general public.

Public perception
How the public understands, and responds to, bioengineering advancements will create or quell demand. This is especially true for food and beverage, consumer packaged goods, beauty and fashion, over-the-counter medicines and vaccines, and new therapeutics.

R&D developments
The pace of new research breakthroughs can't be scheduled to coincide with a board meeting or earnings report. There are factors that can improve the likelihood and speed of new discoveries (funding, quality and size of staff, access to resources). We closely monitor R&D developments but treat them as wild cards.

OPPORTUNITIES & THREATS

Threats

There is no alignment on a global framework governing bioengineering. As a result, you can anticipate geopolitical conflict stemming from the development and use of emerging bio-based technologies in the years to come.

Unresolved IP and patent issues in biotechnology raise serious concerns about how patenting practices could hinder biotech development across various countries.

While new agricultural methods may benefit the environment, they pose threats to local communities in economies still reliant on traditional farming practices.

CRISPR therapies may not be universally accessible, potentially deepening global health divides and exacerbating current disparities, leading to worsened conditions and future conflicts.

Engineering novel organisms and using techniques like germline editing risks uncontrollable cascading effects in nature, potentially creating invasive species or pathogens, turning a lab accident into an ecological disaster.

Opportunities

In the coming decade, biotech advancements will cause leaders to confront their core beliefs about their business models, products, and services. In the meantime, it's imperative that businesses seek out new partnerships, develop new pipelines for talent, and align stakeholders on the moral and ethical uses of engineered biology.

Because bioengineering has been evolving over decades, it may seem premature for action, but its advancements will compound. Like AI, which grew quietly before becoming essential, bioengineering will soon be integral to operations. Leaders paying attention to its progress and harnessing strategic foresight can gain first-mover advantages.

Biotech companies always face capital needs, particularly amid sector-wide valuation challenges. Streamlining R&D, general, and administrative expenses—as well as exploring new financing options, and considering mergers with other biotechs—can help them navigate the current market landscape.

Businesses should start exploring white spaces now. Where are the opportunities for innovation and growth? What might threaten the organization's ability to thrive? Where are there downstream risks to partners or customers? Businesses that seek out and anticipate near-term developments will gain a competitive advantage.

Generative biology (genBio) will unlock new ways to develop medicines, food, agricultural systems, beauty and skincare products, textiles, packaging and building materials, and more. Leaders should develop scenarios for using and scaling these genBio systems, processes, and products.

INVESTMENTS AND ACTIONS TO CONSIDER

1

As companies consider AI's impact on their workforce, they are neglecting to focus on future demands for individuals skilled in both AI and biology. Companies across various sectors should proactively develop insights into their future workforce requirements and start establishing the necessary talent pipeline now.

2

As VC investment floods into groundbreaking biotech platforms this year, companies must distinguish themselves by clearly defining their uniqueness. Also crucial is broadening their focus from rare to major unmet medical needs, ensuring a solid value proposition to secure crucial VC funding for drug approvals.

3

As the biotech ecosystem evolves, life sciences and other companies will need to undertake a new digital transformation that includes AI. This should include the creation of a long-term strategy, an expanded value network map, and a comprehensive execution plan to stay competitive and innovative.

4

The AI-bio convergence will spark myriad innovations and demand unprecedented agility from companies. Leaders must empower their organizations to experiment with new products and processes, and ensure that they shape their own futures rather than being compelled to adapt to external innovations or react to regulatory shifts.

5

The uncertain regulatory landscape offers a unique opportunity for business and government to collaboratively envision the future. Regulation is reactive. Stakeholders can proactively evolve frameworks to address safety, update IP and copyright processes, align on commercialization strategies, and thwart misinformation.

6

To stay competitive, companies must use strategic foresight to understand how the evolving biotech ecosystem could impact their existing products and processes. Leaders should prioritize monitoring, acting, and agile decision-making in order to adapt to the AI-bio convergence.

CENTRAL THEMES

Gene Editing Realizes Its Promise

CRISPR's journey to commercial success has been a marathon, not a sprint. For more than a decade, the gene-editing technology faced many hurdles, from technical challenges to patent disputes to regulatory approval, slowing its path to practical applications. Finally, in 2023, CRISPR's promise crystallized with the approval of Casgevy, a first-of-its-kind therapy for sickle cell disease in the UK and US. This landmark therapy, which deactivates a specific gene, highlights CRISPR's ability to disable genes with precision. More importantly, with government clearance and a real-world use case, Casgevy opened the door to a vast array of possibilities for gene editing and other biotechnology applications. However, as CRISPR therapies move toward broader application, challenges remain: namely, the complexity and cost of treatments, accessibility issues, and public trust. Despite these obstacles, CRISPR's trajectory toward commercialization marks a significant milestone—though the marathon continues.

AI and Biology Are Converging

Increasingly, AI is being used in biological systems. Scientists are no longer limited by a traditional human team's speed: New AI models now accurately predict biological structures, a capability that will accelerate scientific research that used to take decades. The AI-bio convergence extends into computing itself, and researchers are exploring the creation of biology-powered machines. These innovative systems promise to be faster, more efficient, and consume significantly less energy than traditional computers. Organoid intelligence aims to use human brain cells in a new type of computer. Programmable DNA computers execute complex operations through molecular manipulation. Some researchers believe this fusion of computers and biological processes is the real future of artificial intelligence; both are important because they offer novel approaches to problem-solving and unlock new forms of creativity. Biological computers potentially open up unprecedented opportunities to improve compute power, data storage, and sustainability.

Businesses and Governments Aren't Prepared

Businesses and governments need to catch up as AI and biology converge. Biotech fields are making discoveries that not only deepen our insight and create new options—they also introduce novel methods to alter biological systems, with outcomes that remain unpredictable. Such progress presents vast opportunities for investment and for businesses to meet their ESG goals. However, it poses challenges for incumbents in supply chain management, agriculture, consumer packaged goods, health, and biosciences that may not see their value networks changing early enough to take action. Cyberbiosecurity is a growing and unmet need, as increasingly companies will need to protect the biotech ecosystem from unauthorized access, damage, attack, and other threats. As new biotechnologies emerge, a lack of alignment on purpose and policy could result in the situation we see today with AI. Without strategic foresight to prepare for the future, the potential risks associated with biotechnological advancements could surpass those of AI, underscoring the urgent need for readiness.

ONES TO WATCH

Dr. Amy Trejo, director of R&D and responsible materials innovation at Procter & Gamble, for leveraging bioengineering for sustainability in the consumer packaged goods space.

Dr. Arthur Levin, distinguished scientist at Avidity Biosciences, for engineering a new RNA platform that delivers therapy to previously inaccessible tissue and cell types.

Dr. Cheryl Cui, CEO of Bota Biosciences, for launching a new type of engine for biological programming and discovery.

Chris Abbott, CEO of Pivot Bio, for scaling sustainable biotech solutions to meet global agricultural challenges.

Dr. Demis Hassabis and **Dr. Shane Legg,** co-founders of DeepMind, for their groundbreaking AI inventions that predict biological structures and combinations.

Didier Toubia, CEO and co-founder of Aleph Farms, for achieving the world's first government clearance to produce and sell cultured beef.

Dror Bin, CEO for the Israel Innovation Authority, for scaling innovation resources in biotech and other critical technologies.

Eben Bayer, co-founder and CEO of Ecovative, for innovating business models to integrate mycelium technology into the production of food and materials.

Dr. Emily Leproust, CEO of Twist Bioscience, for breaking new ground in high-throughput synthesis and sequencing of DNA.

Dr. Gaurab Chakrabarti, CEO of Solugen, for decarbonizing the chemicals industry.

Dr. Hal Barron, Dr. Rick Klausner, and **Hans Bishop,** founders of Altos Labs, for leading a new effort on cellular rejuvenation programming to reverse the human aging process.

Dr. J. Craig Venter, CEO of JCVI and serial entrepreneur, for advancing the fields of synthetic biology and genomic research.

Dr. Jason Kelly, co-founder and CEO of Ginkgo Bioworks, for scaling genetic engineering to produce bacteria with a wide variety of applications.

Dr. Jianmin Fang, co-founder and executive director of RemeGen, for overseeing one of the largest partnership deals between a Chinese biotech company and a Western company (Seagen) in history.

Josh Tetrick, co-founder and CEO of Eat Just, for commercializing cultured meat in the US and Singapore.

Dr. Kimberly Smith, R&D chief at ViiV Healthcare, for her work to end the HIV epidemic through her visionary practices and innovative approach to clinical development.

Dr. Lisa Dyson, founder and CEO of Air Protein, for her work developing food from carbon dioxide.

Dr. Mary Maxon, executive director of BioFutures at Schmidt Futures, for developing and leading a new program to maximize the potential of biotech for a circular bioeconomy.

Matthew McKnight, general manager of biosecurity at Ginkgo Bioworks, for his role in advancing biotechnology for national security, public health, and pandemic preparedness.

Niyati Gupta, CEO of Fork & Good, for building and scaling new business models in food and agribusiness.

Dr. Noubar Afeyan, CEO of Flagship Pioneering, for inventing and building platform companies, each with the potential to transform human health and the planet.

Dr. Raymond Deshaies, senior vice president for global research at Amgen, for his work on a new frontier of small molecule design via RNA degradation.

Dr. Sarah Reisinger, chief science and research officer for DSM-Firmenich, for her continued work bridging the gap between R&D, technical requirements, and commercialization.

Dr. Yin Ye, CEO and executive director of BGI Group, for scaling the industrial application of cutting-edge biotechnology and genomics research.

IMPORTANT TERMS

BIOENGINEERING DOMAINS

Innovations in biotechnology are currently defined by five key areas: biomolecules, biosystems, biomaterials, biocomputing, and biomachine interfaces. Major breakthroughs in one field either reinforces or accelerates breakthroughs in the others.

Biocomputing

Biology is made up of code—and the goal is to harness that code for computing. DNA and RNA can be used as mediums for storing information and data processing. While traditional supercomputers use a lot of energy, heat up quickly, and require costly cooling centers to function properly, biological computing systems can perform computations without burning excess energy—and they are infinitely scalable.

Biomachine iInterfaces

Innovative new interfaces are connecting living organisms to computers for many different purposes, from restoring a stroke victim's ability to walk to someday controlling external computers simply using thought.

Biomaterials

It is now possible to replicate or improve on raw materials using bioengineering technology. One example: a bioreplacement material that is produced sustainably, at a lower cost than traditional raw materials, and poses no harm to the environment.

Biomolecules (also known as omics)

A group of biological sciences collectively known as "–omics," including fluxomics (metabolic reactions in cells), metabolomics (chemical species involved in the reactions in cells), proteomics (the decoded product, or proteins), transcriptomics (the RNA created from each piece of genetic code), and genomics (the DNA code that drives cellular processes) is working to analyze the structure and functions of biological molecules that translate into the function and dynamics of an organism. Learning about and tinkering with the engineering of molecules (think: DNA, RNA) will lead to new therapeutics and innovative defenses against novel viruses, as well as alternatives to the ways we currently grow food.

Biosystems

Biology is complex. Scientists are applying engineering principles to understand and influence the pathways, connections, and interactions within biological systems. Developing new processes could lead to new opportunities to modify or even create cells, tissues, organs, and potentially complex networks like respiratory systems.

ADDITIONAL TERMS

Cas9 (CRISPR associated protein 9)

A special enzyme that can cut DNA sequences. Cas9 is part of the "molecular scissors" method of genome editing made possible by CRISPR.

Chimera

A living organism created by combining cells from at least two genetically different organisms.

Chromosome

A thread-like structure made up of a single length of DNA and found in the nucleus of each cell.

CRISPR (clustered regularly interspaced short palindromic repeats)

A naturally occurring genetic engineering tool found in bacteria that can be programmed to target specific areas of genetic code and to edit DNA at precise locations.

DNA (deoxyribonucleic acid)

A self-replicating two-stranded molecule, arranged as a double helix, that contains the genetic instructions used in the development, functioning, and reproduction of an organism.

Enzyme

A biological catalyst, usually a protein. Enzymes speed up the rate of specific chemical reactions in cells.

Ex vivo

Outside of cells or an organism.

Gain of function (GoF) research

Research intended to modify a biological pathway in a cell line or organism to enhance or increase certain biological functions.

Gene

The basic unit of heredity.

Genome

The complete set of DNA that makes up an organism.

Genome editing

Intentionally altering cells or organisms by inserting, deleting, editing, or otherwise modifying a gene or gene sequence.

Heritable genetic change

Altering genes in a way that results in changes that pass down through generations.

IMPORTANT TERMS

In vivo
Inside of cells or a living organism.

Induced pluripotent stem cells (iPSC)
Cells that have been reprogrammed back into an embryonic-like state with the potential to develop into other types of cells that can be used for therapeutic or reproductive purposes.

Mutation
A change in a DNA sequence.

Off-target effect
Typically an unintended direct or indirect consequence of altering an organism.

Regenerative medicine
An emerging field seeking to repair or replace torn, defective, or missing tissue using stem cells, engineered cells, or biological processes.

RNA (ribonucleic acid)
A messenger chemical that carries instructions or translates the genetic code of DNA into structural proteins.

Stem cell
Nonspecialized cells that have the ability to develop into other types of cells with specialized functions.

Synthetic biology
A field of science rooted in both biology and engineering that seeks to redesign organisms, or design new organisms, to have new abilities.

AI AND BIOLOGY

AI AND BIOLOGY

Pharmaceutical Companies Invest in AI

Historically, scientists struggled to mine big biological data sets for insights using conventional statistical tools. With the spotlight now on AI, drug developers now see they're failing to capture the value of their important asset: their data. AI's potential to refine the often unpredictable process of drug discovery is significant, since even marginal enhancements can substantially improve the speed and efficiency of developing new drugs. Two years ago, DeepMind's AlphaFold made a notable breakthrough in predicting protein structures, an advancement that will soon revolutionize the process of identifying molecules with therapeutic potential. But the practical application of AI in drug development is already underway. AstraZeneca now uses reinforcement learning in 70% of its small molecules in development. London-based biotech startup E-therapeutics uses AI to design RNA molecules and algorithms to predict their likely activity, in an effort to thwart disease-causing genes. Investment bank Morgan Stanley projects that within the upcoming decade, the pharmaceutical industry could spend roughly $50 billion a year on AI to propel every stage of new drug development, from ideation to compound identification to clinical trial design and marketing.

Generative AI Gains Wide Acceptance

Just a few years ago, the pharmaceutical and life sciences industries weren't all that interested in investing in or using AI to automate and improve various processes. Last year, when genAI took center stage, that resistance started to fade, especially in the Asia-Pacific region where genAI startups are particularly active. Singapore's Integrated Health Information Systems entered a pivotal partnership with Microsoft and OpenAI, which will create a health care–specific GPT hosted on Azure. Once it's finished, this initiative aims to enhance the efficiency of health care workers by providing valuable insights and automating tasks. In Japan, the introduction of an advanced genAI tool is transforming the way doctors process extensive patient interviews. Tokyo-based Ubie is a startup that makes AI-based health care products, hospital SaaS products, and AI symptom checkers. As genAI technologies continue to evolve and integrate within the pharmaceutical and life sciences sectors, strategic shifts in how health care and medical research are conducted and managed will occur.

Text-to-Synthetic Compound: LLMs Automate Chemistry

While you were asking GPT-4 to write the lyrics for a rap song about avocados, researchers have been enhancing the capabilities of large language models to automate complicated tasks in chemistry. One such researcher is Philippe Schwaller, from the Swiss Federal Institute of Technology in Lausanne, whose team gave GPT-4 access to extensive databases of molecules, chemical reactions, and scientific research. They call the new system ChemCrow, and they're using it on a wide range of chemistry challenges, including drug synthesis and cost calculation. ChemCrow successfully devised a practical plan for synthesizing atorvastatin, a drug for high blood cholesterol. On average, ChemCrow achieved over 9 out of 10 in human evaluations for 12 chemistry tasks. Separately, Gabriel Gomes at Carnegie Mellon University and his colleagues also upgraded GPT-4 with similar chemistry tools—with a twist. This model is integrated in a remotely controlled chemistry lab with liquid compounds that could be mixed using robotic arms. They asked the system to perform certain reactions by writing in a prompt, which was then executed by the robotic arms in the lab. But when the team asked the system to whip up sarin gas, the model—mercifully—refused. While AI promises a new pathway to automate the process of synthesizing compounds, it's not without potential danger. Public domain tools could be used to create something potentially dangerous.

AI-Generated Proteins

An AI system can now create new types of proteins that don't exist in nature. By focusing on the protein's amino acid building blocks, researchers can design a protein with special properties—like being really tough or flexible—to make new materials that are like plastics but better for the environment. Recently, ex-

AI AND BIOLOGY

perts have made AI programs that can guess the 3D shape of a protein from its amino acid sequence. But figuring out the best amino acid sequence to engineer a certain protein shape is much harder. Researchers from MIT, the MIT-IBM Watson AI Lab, and Tufts University used a generative AI model not unlike DALL-E 2, which generates realistic images from natural language prompts. Then, they adapted the model so it generates amino acid sequences of proteins that achieve specific structural objectives. The researchers used this architecture to build two machine learning models that can predict a variety of new amino acid sequences that form proteins meeting structural design targets. Meanwhile, researchers at the University of Washington's Institute for Protein Design Baker Lab created a new program, called RFdiffusion, which allows scientists to upload a 3D model of a cell and use software to identify the most likely candidates for drug testing. RFdiffusion increases the accuracy as much as 100-fold, compared to previous protein design programs that didn't use AI.

Generative Biology

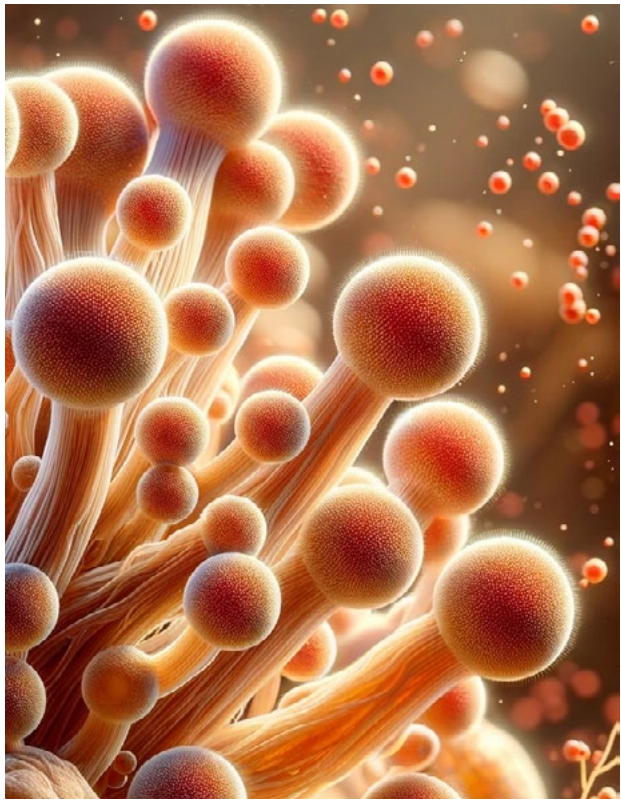
What if it was possible to generate novel protein therapeutics using new computational tools, without having to discover them through trial and error? That's the promise of Boston-based startup Generate Biomedicines, which trained an AI to invent proteins with structures that, as far as we know, don't exist anywhere in nature. Inspired by DALL-E 2, the powerful text-to-image AI system from OpenAI, Generate's platform asks the user to describe the shape, size, and function of a protein they'd like to see. It then uses diffusion modeling to generate a structure with the right amino acids folded correctly to meet the description. Our understanding of the genome, along with fundamental molecular and network mechanisms, is now being enhanced by innovative tools that allow us to interact with, examine, and manipulate biological systems in new ways.

Simulating Molecular Interactions

Increasingly, companies are using AI-powered simulations in place of the physical testing of drug compound candidates. This new approach circumvents the traditional, often prohibitively expensive, methods of chemistry-based experimentation. But the use of AI in this context is not just a matter of cost-efficiency; it marks a transformative step in bioengineering. By simulating molecular interactions on computers, researchers can rapidly iterate and refine drug compounds, significantly accelerating the development process. This method offers a more sustainable, scalable, and potentially more accurate alternative to physical testing. What's on the horizon: much faster, cheaper R&D. Our analysis suggests that organizations that adapt in silico molecular simulations powered by AI will gain a competitive edge—and be prepared for knock-on effects that make up the broader movement toward a more innovative, data-driven approach in bioengineering and health care.

Spatial Biology Improves with AI

Spatial biology is a burgeoning field predicated on gaining a deeper understanding of



A close-up view of fungal hyphae and spore structures. As AI and biology converge, it will be possible for scientists to iterate on nature's designs.

AI AND BIOLOGY

the human body using computer modeling and generative AI. Spatial biology's core lies in examining cells and tissues within their natural 2D or 3D habitats, akin to how GPS technology pinpoints locations. It leverages cellular and molecular data to map the intricate architecture of cells, allowing for a much more comprehensive understanding of cellular interactions in their environment—a perspective traditional methods like bulk sequencing cannot offer. Why bother examining cells in super-high resolution? Because a closer look will reveal complex cellular interactions and functions, with the potential to reach molecular or atomic level insights as the technology improves. And increasingly, spatial biology will produce complex data, and companies will need advanced algorithms to help mine it for insights. The field is at the cusp of transforming our understanding of cellular mechanics and disease pathology. Just as the James Webb Telescope, with its super-high-resolution images, is changing our understanding of the universe, the technological advancements, improved automation, and sophisticated data analysis capabilities researchers will gain from spatial biology will transform our understanding of life. The full potential of spatial biology in diagnostics and treatment development will usher in a new era of precision medicine. This represents not just a leap in medical science but also a paradigm shift in our approach to health care and disease management.

Emerging biotechnology techniques will allow scientists to create hyphae-like structures for any number of new purposes.

Image credit: Future Today Institute and Dall-E.

GENE EDITING & CRISPR

GENE EDITING & CRISPR

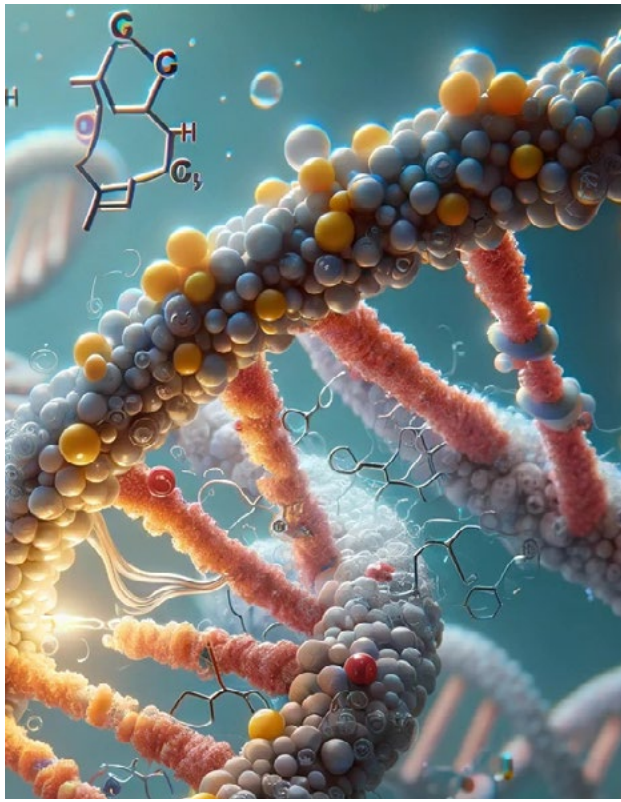
CRISPR Treatment for Diseases

Both the US Food and Drug Administration and the UK medicines regulator have finalized their groundbreaking approvals of the first CRISPR gene therapy for Casgevy, a therapy built on the CRISPR-Cas9 gene editing tool. Casgevy targets sickle cell disease and β-thalassaemia, conditions characterized by severe pain and the need for regular blood transfusions. These approvals will pave the way for future CRISPR therapies to potentially cure a wide range of genetic diseases. CRISPR technology, which earned its creators Dr. Emmanuelle Charpentier and Dr. Jennifer Doudna the Nobel Prize in chemistry in 2020, is used in Casgevy to correct gene mutations responsible for sickle cell disease and β-thalassaemia. These mutations affect hemoglobin in red blood cells, leading to serious health complications. To administer the treatment, doctors first draw blood-producing stem cells from patients and then use CRISPR-Cas9 to precisely edit the hemoglobin genes. Casgevy targets the BCL11A gene, which normally inhibits the production of fetal hemoglobin. By disrupting BCL11A, Casgevy triggers the production of a stable form of hemoglobin, alleviating the symptoms of these diseases. The treatment process involves preparing the patient's bone marrow to receive the modified cells and a subsequent period of hospitalization to ensure the cells' effective integration. While the treatment is effective, its future widespread use is still in doubt. CRISPR therapies are expensive and difficult to scale, due to the complexity and technological requirements of treatments, including the extraction, modification, and reinsertion of blood stem cells. In the near term, this will likely hinder their use in low- and middle-income countries. While Casgevy could serve as a catalyst for further R&D in gene editing and potentially transform the future of medical treatments, there is a pressing need for continued innovation and investment to make such groundbreaking therapies more universally accessible.

Next-Generation Gene Editors

While CRISPR-Cas9 has been groundbreaking in enabling precise DNA cutting, its application is somewhat limited to diseases that can be addressed by gene disruption. The future of gene therapy lies in more versatile gene editing tools that offer capabilities such as activating genes, altering individual DNA bases, or introducing new genetic sequences.

What's on the horizon: an expansion of the CRISPR toolkit, including base editing, prime editing, and epi-editing. Last year's regulatory approval of CRISPR/Cas9 therapies opened a new pathway to help next-gen gene editing technologies enter clinical trials faster, because the groundwork for navigating the regulatory and technological complexities of novel gene therapies has now been established. We are finally moving from ambition and experimentation to practical application.



In the future, scientists will coax enzymes to interact with DNA bases to produce more precise molecular activity.

Image credit: Future Today Institute and Dall-E.

GENE EDITING & CRISPR

New Editing Tools

Base editing

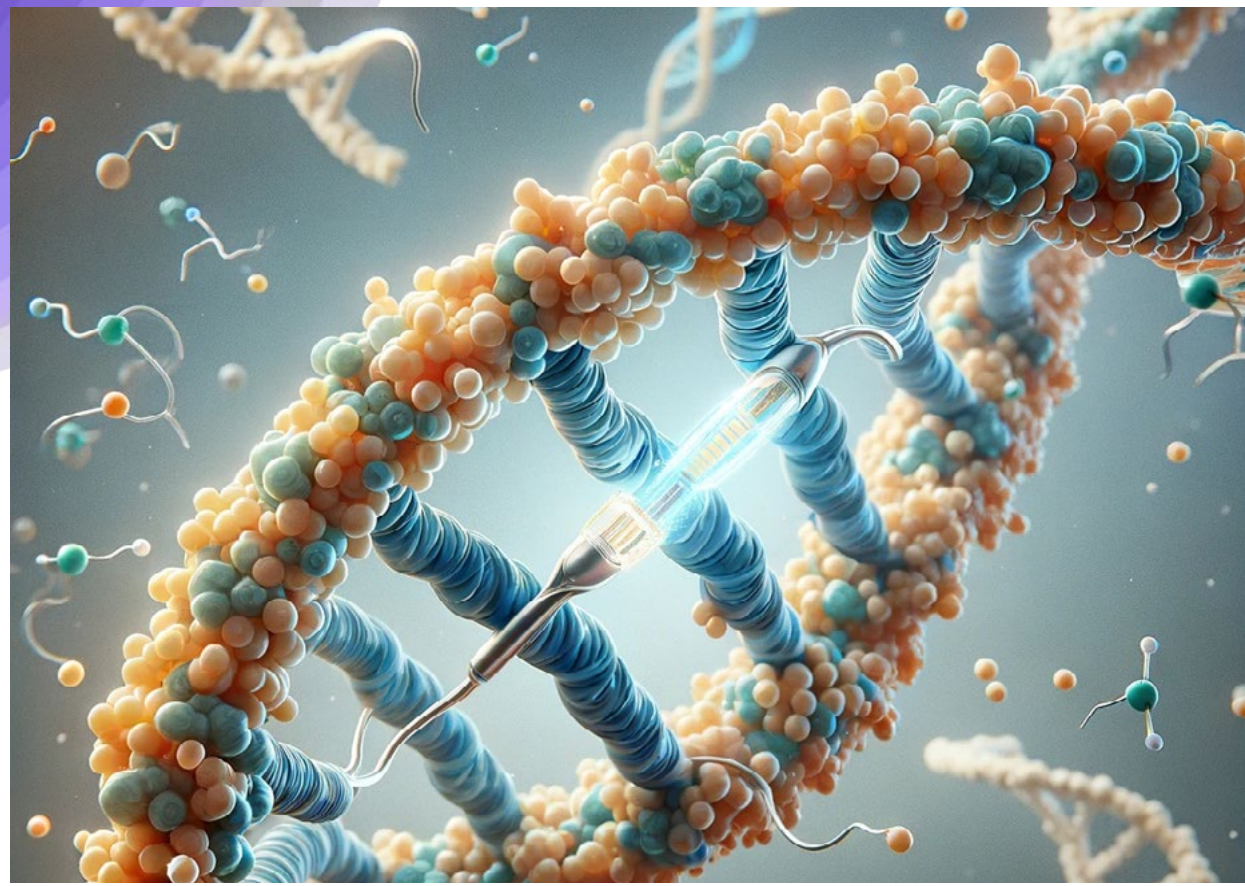
First developed in 2016 by Harvard biochemist David Liu, base editing allows for the precise alteration of individual DNA letters. This technique has shown promise in preclinical studies for diseases like muscular atrophy and muscular dystrophy. Beam Therapeutics, co-founded by Liu, initiated the first US clinical trials in base editing for leukemia treatment, with initial data expected in 2024. Meanwhile, Verve Therapeutics' in vivo base editing trial for high cholesterol has shown encouraging preliminary results, potentially revolutionizing coronary disease treatment.

Prime editing

Also conceived in Liu's lab, prime editing offers even greater precision, capable of deleting or adding small DNA segments. As impressive as CRISPR is, it can sometimes change the wrong genes or accidentally break apart strands of a DNA's double helix. The refinement to CRISPR affords more precision and versatility. Prime editing has demonstrated success in correcting various inherited diseases in animal models.

Epi-editing

Epi-editing is yet another novel CRISPR application that modifies the epigenome to regulate gene expression without altering the underlying DNA. This approach has already gained attention for its potential in treating diseases by editing gene expression regulatory networks. Durham, North Carolina–based Tune Therapeutics has shown promising results in gene silencing using epi-editing, and several companies, including San Francisco–based Epic Bio, plan to commence clinical trials in the near future.



Next-generation gene editors will help expand the CRISPR toolkit, enabling scientists to perform more precise edits.

Image credit: Future Today Institute and Dall-E.

GENE EDITING & CRISPR

In Vivo Gene Editing

It is now possible to inject CRISPR components directly into the body and make changes to genetic material in vivo, or "within the living." Unlike "ex vivo" editing, where cells are modified outside the body and then reintroduced, in vivo editing involves introducing the gene-editing tools (like CRISPR-Cas9) in the body using viral vectors or lipid nanoparticles. Practically speaking, this means that treating cancer would no longer require traditional chemotherapy—instead, cancerous cells would be targeted and edited with CRISPR. The FDA approved a phase 3 trial by New York–based Regeneron Pharmaceuticals and Cambridge, Massachusetts–based Intellia Therapeutics, which was co-founded by Dr. Jennifer Doudna. Their therapy, NTLA-2001, is a groundbreaking one-time intravenous treatment designed to target liver cells and specifically aims to disable a gene responsible for a progressive and fatal disease. Early clinical trials of NTLA-2001 have shown remarkable results, reducing disease-causing protein levels by up to 93%, with these reductions remaining stable for at least nine months.

These promising outcomes have also been replicated in a variant of the disease affecting heart tissues. Though the trial isn't expected to deliver concrete results until 2027, its impact is already being felt. This is the first published instance of CRISPR being used directly in the bodies of a large group of individuals, marking a pivotal moment in the field of gene editing. While this clearly means a big leap forward, it also raises concerns about potential off-target effects and the implications for germline cells, which are critical for reproductive functions.

Cell Therapy 2.0

For more than a decade, researchers have transplanted healthy, viable cells to replace or repair damaged ones. Most notably, cellular therapy has shown promise in helping a person's immune system fight cancer. But cellular therapy carries associated risks, which range from flu-like symptoms to death. The field is evolving, and two emerging techniques are pushing cell therapy into its next era. One is in vivo cell therapy, which helps patients produce cells that can bind to specific proteins on the surface of cancer cells. Researchers at the Nanfang College of Sun Yat-sen University and Huazhong University of Science and Technology (both in China) loaded nanocarriers with a new set of genetic instructions and successfully regressed leukemia in a mouse. The second technique involves engineering synthetic gene circuits in order to protect healthy cells when delivering cellular therapy. CAR T cells, or white blood cells that have been genetically modified in a lab to help fight cancer more effectively, can be lethal to cells they come into contact with, whether they're cancerous or not. A new method of controlling cell therapy, using engineered networks, would offer doctors better precision.

Cells have complex structures that can be studied and manipulated using bioengineering techniques.

Image credit: Future Today Institute and Dall-E.

READING & SEQUENCING GENOMES

READING & SEQUENCING GENOMES

Next-Generation Genome Sequencing

When the first human genome was sequenced in 2003, it cost roughly $2.7 billion and took 13 years to complete. In 2012, it cost about $10,000 for researchers to sequence a full genome, and today, you can sequence your genome from the comfort of your home for less than the price of a Black Friday TV deal. The next generation of sequencers will offer a monumental leap forward in speed and efficiency, akin to the transition from dial-up to high-speed internet. On the horizon: ion semiconductor sequencing, which converts chemical information into digital data; nanopore sequencing, a technique that reads molecular letters through tiny nano-size pores; and single-molecule real-time sequencing, which observes the DNA replication process in real time. Ion Torrent, made by Thermo Fisher Scientific, automatically turns the basic building blocks of DNA (represented by the letters A, C, G, T) into a form that computers can understand (0s and 1s)—and it does it right on a tiny semiconductor chip. This method combines straightforward chemistry with advanced chip technology offering a new way of reading DNA that's not only easier and faster but also more affordable and adaptable than what we've had. Just as the microprocessor revolutionized computing, shifting us from large, centralized mainframes to personal desktop computers, semiconductor technology is set to make DNA sequencing much more accessible, allowing even small labs and clinics to have this powerful tool at their disposal. This could transform many industries, just like semiconductor chips did for electronics. Oxford Nanopore makes devices for nanopore sequencing that relays information in real time. Unlike traditional DNA sequencing methods, where scientists have to wait until the end of the process to get any data, nanopore sequencing lets them see the results as they happen. This is great for urgent situations, like identifying harmful bacteria or viruses quickly. And once scientists have the information they need, they can stop the sequencing. This means labs can clean and reuse their equipment (called a flow cell), which is both time-efficient and cost-effective. These methods, each unique in its approach, are pushing the entire field of sequencing forward.

Metagenomics

Metagenomics represent a new approach in a genomic analysis. Simply put: imagine metagenomics is like dealing with one box full of 10 different jigsaw puzzles. In this analogy, each puzzle represents the DNA of a different organism living in a particular environment. The challenge of metagenomics is to sort out these pieces and put together each individual puzzle correctly. As researchers are considering new therapies or trying to understand how a virus or pathogen works, they need contextual data to understand cause and effect. New metagenomics tools help scientists solve several puzzles at once to understand the diverse range of life forms coexisting in a specific environment. This is crucial for gaining insights into how these microorganisms interact with each other, with humans, and with the environment. It's a complex task but offers valuable information for various applications, from health care to environmental science. For example, metagenomics can detect viruses on food items, like identifying viral contamination on lettuce. This helps trace the source of microbial and viral contamination, improving food safety. It's effective in cleaning up pollutants, by helping to identify microorganisms in polluted environments that can degrade toxic substances more efficiently than other methods. And it's being used to identify how microorganisms compete and communicate in different environments, from human digestive tracts to deep-sea vents. Israel-based BiotaX developed TaxonAI, a platform that can collect, analyze, and predict multiple disease states and calculate optimal interventions supported by metagenomic AI analysis. Chile-based KITAI's lab-on-a-chip combines AI, microfluidic, and metagenomics technologies to identify biological pests, monitor water sources, and analyze environmental pathogens.

Faster Gene Synthesis

Synthesis transforms digital genetic code into molecular DNA, allowing scientists to design and mass-produce genetic material. Twist Bioscience is a pioneer in the field; it's formed

READING & SEQUENCING GENOMES

as many as 300 base pairs of DNA, and these snippets, or oligos, can be joined together to form genes. Both the price for oligos and the time to produce them is decreasing—while base pairs are getting even longer and more complex. It now costs an average of just 7 cents per base pair—a 22% decrease year-over-year. Twist's DNA snippets can be ordered online and shipped to a lab within days; the synthetic DNA is then inserted into cells to create target molecules, which are the basis for new food products, fertilizers, industrial products, and medicine.

Quantum Biology

Quantum biology is an emerging field that combines quantum physics—the science of the very small—with biology, the study of living things. Researchers apply the principles that govern subatomic particles and to understand how living organisms work at a fundamental level. For business leaders, this matters because quantum biology has the potential to revolutionize various industries. It can lead to breakthroughs in medicine, by improving drug design or understanding diseases at a molecular level. In technology, it could inspire new, more efficient ways of data processing and energy storage. It's an exciting frontier that blends the most basic elements of our universe with the complexity of life, opening up a world of possibilities for innovation and advancement in multiple fields. One experiment has already yielded results: At the Johns Hopkins University Applied Physics Laboratory in Maryland, researchers found striking similarities between an enzyme central to human metabolism and a magnetically sensitive protein found in birds. This deepens our understanding of magnetosensitivity—but in practical terms, it also potentially transforms our approach to studying biological navigation mechanisms.

Using the Human Genome Map

When the first human genome was deciphered two decades ago, it was mostly—but not entirely—complete. That's because roughly 200 million base pairs of DNA, or about 8% of the human genome, weren't yet readable by sequencing machines because they had repeating segments or were simply too challenging to be recognized and cataloged. As technology improves, so will our ability to map a more detailed version of human life on a granular scale. The Telomere-to-Telomere Consortium, aptly named after what's called the end caps of chromosomes, published a new set of papers in 2022 that identified all but five of the hidden areas of the map. Using various sequencing technologies, including a novel nanopore device capable of reading 100,000 bases at a time alongside a sequencer with improved accuracy, researchers discovered new areas for gene evolution. In 2024 and beyond, scientists will gain new insights into regions of the human genome that haven't been fully explored, and that should in turn reveal discoveries about human evolution, longevity, and resiliency. Meanwhile, the National Institutes of Health has initiated a groundbreaking program with an initial investment of $6.4 million to establish Diversity Centers for Genome Research at three institutions: the University of Texas Rio Grande Valley, Meharry Medical College, and the University of Hawai'i at Mānoa. With this move, NIH is targeting colleges and universities with a history of serving underrepresented communities that haven't recently received significant NIH funding; the goal is that these centers will enhance the universities' research capabilities and inspire students from diverse backgrounds to pursue genomics. This initiative, part of the National Human Genome Research Institute's $32.7 million commitment over the next five to seven years, reflects a strategic move to diversify the genomics field, recognizing that diverse perspectives spur creativity and innovation.

Unlocking Bioinformatics Data

Rapid advancements in technology and a steep decline in sequencing costs are advancing the use of bioinformatics data. Scientists use this data—biological information stored digitally, primarily focusing on genetic and molecular data—to investigate all sorts of questions: How do certain diseases affect our bodies at the molecular level? Can we design new medicines to treat these diseases? How do different species evolve and adapt to their

READING & SEQUENCING GENOMES

environments? But there are challenges in understanding it. Sequencing an individual's entire genome now generates a staggering 100 gigabytes of raw data, a figure that more than doubles post-analysis with the application of deep learning and natural language processing tools. This will result in a deluge of data that experts estimate will need 40 exabytes for storage by 2025—that's eight times the storage required for every spoken word in human history. Genome analysis pipelines are struggling to keep pace with this explosion of data. The complexity and computational intensity of sequencing analysis, which involves myriad steps to identify genetic variations, are monumental tasks requiring sophisticated technological solutions.

Recent advances in deep learning and AI generally are significantly improving the process of DNA sequencing, making it faster, more accurate, and less expensive. Nvidia, which makes powerful GPUs, is applying AI to both traditional (short-read) and newer (long-read) DNA sequencing methods. This is making it possible to sequence human genomes with high accuracy at a much lower cost. Reading, sequencing, and analyzing bioinformatics data using technological breakthroughs have practical, real-world applications, such as quickly identifying genetic disorders in newborns or discovering new targets for drug development.

Sequencing Ancient Genomes

Archaeology and genetics are merging, hoping to surface new insights about the history of life on Earth. The field of ancient DNA (aDNA) research is starting to uncover a wealth of insights, from identifying new branches of the human family tree to revealing the genomes of long-extinct species. For example, recent breakthroughs have traced the origins of the Black Death to present-day Kyrgyzstan and revealed lost Indigenous populations. The sequencing of ancient animals and humans, from woolly mammoths to Neanderthals, has provided a genetic window into bygone eras. The 1000 Ancient Genomes project, led by Pontus Skoglund at the Francis Crick Institute in London, recently analyzed the DNA of a 10,000-year-old skeleton found in Somerset, England. The sequence showed that he likely had dark skin and blue eyes, a genetic combination that might have been common millennia ago but today is rare. This expansion of the genetic diversity map goes beyond modern populations, offering insights into how species have evolved and adapted over millennia. But the impact of aDNA extends beyond biology and archaeology; it fosters cultural and political connections, enhancing our collective understanding of the human journey. Sequencing ancient genomes will help historians develop a more accurate understanding of what society might have been like thousands of years ago and how we compare today. As technology evolves, aDNA research not only allows us to revisit the past, it holds the key to unlocking future discoveries, making it an invaluable asset in the quest for knowledge about the human experience.

Programmable Gene Editing Proteins

Researchers at the Massachusetts Institute of Technology found that certain eukaryotic organisms (like plants, animals, and fungi) have special enzymes that can cut DNA, similar to how CRISPR technology works. These enzymes, which seem to be related to some CRISPR proteins, could potentially be used to edit human DNA, which means they could play a big role in future medical treatments and research. One team at MIT, led by Feng Zhang, focused on systems in eukaryotes called OMEGAs (Obligate Mobile Element Guided Activity), which could move small bits of DNA throughout bacterial genomes. They discovered proteins called Fanzors in various organisms, which are capable of editing DNA. These Fanzors are smaller than typical CRISPR proteins, making them potentially easier to use in therapies. Although they're not as efficient as current CRISPR methods yet, the team has already improved their performance significantly. This research could lead to new ways of editing genomes more efficiently and perhaps with fewer side effects.

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

Bioprinting Electronics

In a groundbreaking development that blurs the lines between biology and technology, researchers at UK-based Lancaster University successfully 3D printed glowing shapes inside nematode worms, demonstrating the potential to embed electronics directly within living organisms. The team leveraged a photonic 3D printer and a special ink that shapes and activates the material within the organism. By feeding this ink to nematode worms, the team was able to create intricate conductive circuits in the form of stars and squares inside the living worms. This technique suggests potential for improving traditional electronic implants, such as pacemakers and bionic ears, which have transformed medical treatments but come with their own set of challenges, including infection risks and maintenance difficulties. The Lancaster University team's work is part of a growing trend in bioprinting electronic implants and computer-brain interfaces, which could replace the medical devices we use today.

Bioprinting and Tissue Engineering

There is a critical shortage of organ donations, and until now, the only path to organ transplantation involved matching with a donor, making sure the recipient's immune response doesn't reject the organ, and mitigating the risk of infection. An emerging solution is organ bioprinting, which leverages stem cell technology to fabricate organs tailored to the recipient's cellular profile, and in turn, should reduce the risk of rejection. Researchers at Stanford University received a landmark federal contract from the Advanced Research Projects Agency for Health to grow human organs inside of bioreactors, which are machines that provide a biologically active environment where cells, tissues, or microorganisms can be grown or maintained under controlled conditions. The team will grow all the cell types needed to produce a human heart inside the bioreactor and eventually feed the cells into a bioprinter to fabricate a fully functional human heart. It's estimated that bioreactors could produce needed cells by the billions, and eventually print a heart every two weeks. This year, printed human hearts will be transplanted into live pigs to see if they can keep the animals alive. Meanwhile, scientists at Harvard University's Wyss Institute have developed a new 3D bioprinting technique for tissue. This method creates thick, vascularized tissues using living human cells consisting of a special silicone mold to shape and support tissue on a chip. In the mold, they first print a network of large blood vessel channels with endothelial cells in silicone ink. Then, they add another layer with mesenchymal stem cells in a different print. Finally, they fill the remaining spaces with a liquid containing fibroblasts and extracellular matrix, creating a connective tissue that strengthens the whole structure. Tissues are about 10 times thicker than those made before and can last up to six weeks.

Fabricating Organoids

It's difficult and dangerous for scientists to study how living human tissue responds to viruses, medications, or other stimuli, because brain or heart tissue can't be removed from a living person. As an alternative, scientists are creating organoids—tiny three-dimensional, multicellular clusters grown from human stem cells that resemble complex tissues like the heart and kidney. In December 2023, scientists at Weill Cornell Medicine used an organoid model to identify a new pancreatic cancer treatment. A month later, scientists at the Princess Máxima Center for Pediatric Oncology in the Netherlands successfully grew tiny brain organoids in a dish from human fetal brain tissue. They also revealed that the tiny blobs of tissue could be reprogrammed to have certain diseases, in order to study developmental disorders or brain cancers. Scientists are already experimenting with transplantation: In separate experiments, researchers at Stanford and the University of Pennsylvania successfully transplanted human brain organoids into damaged rat brains. The organoid made connections to the rest of the brain and responded to flashing light stimuli. This raises both complex ethical concerns and, perhaps, fears of a day when super-rats emerge that can process information as well as humans. This area of research is controversial in some countries, including

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

the US, where bills introduced into both the Senate and in many state legislatures call for a ban on any research involving fetal tissue, even if it was cultivated in a lab.

Growing Organoids to Study Long COVID

Organoids are being used to research the lasting effects of SARS-CoV-2, the COVID-19 virus, in addition to other respiratory diseases. Miniature brains, lungs, guts, and livers are being grown in high-security labs and infected with the virus, as are combinations of different organs to test therapies and the lasting impacts of long-haul Covid. Scientists at the Karolinska Institute in Sweden infected brain organoids with SARS-CoV-2 and discovered that brain fog could be caused by the destruction of connections between neurons. Neurobiologists at the UK's MRC Laboratory of Molecular Biology in Cambridge used organoids to learn that SARS-CoV-2 damages the protective barrier of the brain. Meanwhile, scientists at the Global Health Institute at Swiss Federal Institute of Technology in Lausanne are studying a harmful bacteria called Pseudomonas aeruginosa, which can cause tough-to-treat pneumonia by forming biofilms, or thick layers, in our lungs. Understanding how these biofilms develop has been difficult. To better study this, the researchers grew mini lung-like structures from stem cells, called AirGels, that mimic the actual environment of our airways, including the presence of mucus and the air-liquid interface found in our lungs. The team discovered that Pseudomonas aeruginosa quickly forms biofilms in connection with lung mucus by pulling the mucus together using tiny, retractable filaments, called type IV pili. This study shows that while mucus normally protects our lung cells, it can also provide a place for harmful biofilms to grow.

Organ-on-a-Chip

Picture something like a computer chip but with a transparent circuit board that's connected to a biological system pumping a blood substitute through tiny blobs of tissue. Organ-on-a-chip systems (OoCs) are synthetic organs made of multichannel, three-dimensional microfluidic cell culture technology that promotes organ functions, processes, and physiological responses. It turns out that these chips are better at predicting real-world responses in humans than the animals typically used in the lab. Researchers in South Korea developed an artificial nervous system that can simulate a conscious response to external stimuli. It includes an artificial neuron circuit, which acts like a brain; a photodiode that converts light into electrical signals; and a transistor that acts as a synapse. All these components are connected to a robotic hand. Think of this as "wetware" rather than computer hardware. This type of a system could help people with certain neurological conditions regain control of their limbs. It could eventually be worn or even embedded. Emulate, a company that makes OoCs, tested 870 human liver-chips across a blinded set of 27 drugs with known toxicity issues—and the chips did a better job of predicting drug safety than the usual methods of studying drug interactions. A team of bioengineers at Harvard made a vagina-on-a-chip using donated vaginal cells. The chip successfully mimicked the vaginal microbiome and is

Originally intended for manufacturing, 3D printing techniques are being applied for human tissue production and printable drugs.

Image credit: Future Today Institute and Dall-E.

BIOPRINTING, ORGANOIDS, AND NOVEL ORGANISMS

actually more realistic than other existing models currently used in labs. OoC academic research and startups are attractive to both venture funding and foundations, which view the technology as foundational to new drug discovery.

3D Printed Drugs

Drug manufacturing today requires enormous facilities and doesn't allow for customization. Emerging techniques using 3D printing technology could improve the variety of medicines offered to patients. For example, Chinese bioprinting company Triastek develops 3D printed medicines and operates the production facilities to manufacture them. Laxxon Medical, based in New York, developed 3D screen printing technology that results in medicines in a variety of shapes intended for oral, transdermal, and implantable formats. Or what about printing medicine at home? Back in 2012, Leroy Cronin, a chemist at the University of Glasgow in the UK, published a paper in the journal Nature Chemistry describing "reactionware," which are 3D-printed chemical vessels containing the components needed to carry out specific reactions. Adding the right starting compounds would set off a reaction resulting in the desired end product. A decade later, Cronin and his team have 3D printed a series of connected containers that perform a variety of chemical reactions. This setup involves 12 different steps, including filtering and evaporating solutions. By carefully adding specific chemicals and liquids at the right times and in the correct order, they transformed basic, easily accessible ingredients into a muscle relaxant known as baclofen. Additionally, by changing the design of these containers and using different chemicals, they were able to produce other medications, such as an anticonvulsant and a drug used to treat ulcers and acid reflux. But it's not clear yet if the authorities that check drug safety will agree to this new method of making medicines. Regulators like the FDA would have to change their safety rules: Rather than just checking the place where drugs are made and the drugs themselves, they would need to make sure that the new equipment used for making drugs actually makes the right medicine.

Bacterial Nanosyringes

In an emerging advancement bridging microbiology and medicine, researchers are transforming bacteria into nanosyringes capable of targeting human cells for precise protein delivery. This innovative approach, redefining the boundaries of targeted medical treatments, could dramatically improve the effectiveness and safety of therapies for many different health conditions, including cancer. Some of our most powerful drugs are made up of small molecules that indiscriminately enter cells and cause unintended side effects. Large molecules like proteins could offer targeted and potent therapeutic benefits, but have one big challenge: they can't get through cell membranes. This is where the bacterial nanosyringes come into play, offering a solution already found in nature. Bacteria like Photorhabdus have evolved cylindrical structures that function like microscopic syringes, injecting their contents directly into targeted cells. Researchers at the Zheng Lab at MIT, led by Joe Kreitz and his team, managed to harness this natural mechanism, using Google DeepMind's AlphaFold AI program to adapt nanosyringes to bind to specific human proteins. This breakthrough technique has already demonstrated its potential in lab settings, successfully delivering various proteins to targeted human cells and even to neurons in mice.

Using Viruses to Deliver Big DNA Payloads

Bacteriophages, also known as phages, are viruses that infect and replicate only in bacterial cells. They are ubiquitous in the environment and are recognized as the most abundant biological agent on earth. Last year, researchers modified a phage to deliver 20 times more DNA to human cells than has ever been possible before in gene therapies. This breakthrough, led by Dr. Venigalla Rao at The Catholic University of America, could unlock new frontiers in cell and gene therapies, enabling complex, multifaceted modifications to human cells in a single treatment step. The virus, equipped to carry DNA strands up to 171,000 base pairs in length, offers an unprecedented capacity to transport not only large DNA sequences but also over a thousand additional molecular components like RNAs

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and proteins. This capability could transition gene therapy from mere treatment to potential cures, especially for complex genetic conditions like muscular dystrophy, which have previously been hindered by the DNA size limitations of existing viral vectors.

Minimum Viable Lifeforms

To understand how new organisms might be created, scientists have long pursued developing an MVP—minimum viable product—for biology. In 2010, scientist J. Craig Venter and his team announced an astonishing discovery: They could destroy the DNA of an organism called Mycoplasma capricolum and replace it with DNA they had written on a computer that was based on a similar bacterium, Mycoplasma mycoides. They named their 907-gene creature JCVI-syn1.0, or Synthia, for short. It was the first self-replicating species on the planet whose parents were, technically, computers, and the project was designed to help the team understand the basic principles of life, from the minimal cell up. In 2016, Venter's team created JCVI-syn3.0, a single-celled organism with even fewer genes—just 473—which made it the simplest life-form ever known. But the organism acted in ways scientists hadn't predicted, producing oddly shaped cells as it self-replicated. Scientists came to believe that they'd taken away too many genes, including those responsible for normal cell division. They remixed the code once again, and in 2021 announced a new variant, JCVI-syn3A. It still has fewer than 500 genes, but it behaves more like a normal cell. Now, researchers are working to strip down the cell even further. They developed a new synthetic organism called, M. mycoides JCVI-syn3B, which evolved for 300 days, proving that it could still mutate. Researchers at Osaka Metropolitan University created a synthetic bacterium capable of swimming by introducing seven proteins into it. With minimal genetic information, the spherical synthetic bacteria are thought to be the smallest mobile lifeform to date. These minimal viable organisms will help researchers design the future of life from first principles.

Organs-on-a-chip are small devices that have tiny pieces of human tissue inside them, and they are specially made to keep the tissues working like they would in the human body.

Image credit: Penn Medicine News.

BIOCOMPUTING & CYBERBIOSECURITY

BIOCOMPUTING AND CYBERBIOSECURITY

Organoid Intelligence

In February 2023, scientists formed a new field, called organoid intelligence (OI), which is now considered the next frontier of biocomputing. To meet AI's growing computational needs, there's a shift away from traditional Von Neumann architecture toward more innovative approaches. One is neuromorphic computing, inspired by the brain's structure, which efficiently handles simultaneous information storage and processing. That's what led researchers at Johns Hopkins to create OI, which uses biological materials—most often human brain cells—for information processing, leveraging their inherent capabilities beyond silicon-based systems. This represents a significant step in harnessing the brain's natural efficiency for AI applications. Late in 2023, a biocomputing system made of living brain cells learned to recognize the voice of one person from a set of 240 audio clips of eight people pronouncing Japanese vowel sounds. The clips were sent to the organoids as sequences of signals arranged in spatial patterns. Why bother inventing technology that sounds like it was inspired by a dystopian sci-fi novel? As the world demands more AI applications like ChatGPT, we'll need more energy-intensive computers and networks to crunch all that data. OI might be able to perform all of those tasks using a fraction of the resources required of a traditional computer.

Training Biocomputers to Learn New Skills

Scientists at the Spanish National Research Council genetically modified a strain of E. coli called Marionette so that it could sense different chemicals and respond to them. But that wasn't all. They modified the strain so its plasmids each encoded for a different fluorescent protein (red and green). While the researchers could alter the ratio of the red and green with future chemical inputs, without inputs, the ratio would simply stay constant and, in a way, was a form of memory. Here's where things got interesting: The team grew the Marionette strain in eight wells that correspond with the outer squares of a grid and taught it how to play tic-tac-toe. Initially, the bacteria played randomly, but the Spanish National Research Council team trained the strain by adding chemicals to the squares—and after eight sessions, the bacteria played at an expert level. While the bacteria haven't yet beat humans at the game, there's an interesting analogy worth remembering: The benchmarks in computing and specifically in AI have always been gameplay. This isn't the only biological computer. A biocomputer called DishBrain learned how to play the 1980s video game Pong. DishBrain is made of ~1 million live human and mouse brain cells grown on a microelectric array that can receive electrical signals. The signals tell the neurons where the Pong ball is, and the cells respond. The more the system played, the more it improved. Cortical Labs is now developing a new kind of software, a Biological Intelligence Operating System (biOS for short), which would allow anyone with basic coding skills to program their own DishBrains. Further demonstrations of new, simple forms of neural networks made from biology will likely occur this year.

Biological Circuits

Scientists are in the process of building biological circuits, made of synthetic DNA, and the software that operates them. A program called DNAr, developed at the Federal University of Mato Grosso do Sul in Brazil, simulates chemical reactions, while another called DNAr-Logic enables scientists to design circuits. A high-level description of a logical circuit is then converted into a chemical-reaction network, which can be synthesized into DNA strands. Dramatically speeding up the design process for biological circuits could drastically reduce the time it takes to discover health treatments and new drugs.

Programmable DNA Machines

In a breakthrough that could redefine computing, scientists at Shanghai Jiao Tong University in China unveiled what might be the world's first programmable DNA computer, capable of executing billions of unique circuits. This could usher in a new era where computers could solve complex mathematical problems and potentially aid in diagnosing diseases. Rather than relying on a traditional silicon microchip-based framework, DNA computers operate using the very molecules that have been nature's medium for storing life's blue-

BIOCOMPUTING AND CYBERBIOSECURITY

prints for eons. After all, biology has a code—ACTG—not unlike binary code (1s and 0s) in conventional computing. But while biology can be expressed in code, DNA is organic—and molecules have a habit of moving around randomly. For that reason, the researchers took inspiration from origami and designed DNA sequences to fold into specific shapes, allowing them to function like parts in a computer, guiding the flow of data. In experiments, they built a DNA computer with 30 logic gates and 500 DNA strands, capable of calculating square roots and identifying genetic markers of kidney cancer.

To be fair, this new DNA computer takes hours to perform simple computations and won't replace regular computers anytime soon. But the research does hold promise for certain biomedical applications. For example, a DNA machine could detect specific genes and respond with a DNA strand that triggers biological reactions, useful in environmental monitoring or disease treatment. What's next: cajoling DNA to perform complex algorithms and disease diagnosis.

Using DNA to Store Data

In 2018, scientists from Microsoft Research and the University of Washington achieved a new milestone: They discovered how to create random access memory on DNA at scale. They encoded 200 megabytes of data on human DNA—including 35 video, image, audio, and text files ranging from 29 kilobytes to 44 megabytes. In 2021, the team built a molecular controller and DNA writer on a chip, with a PCIe interface. Microsoft used the system to store a version of the company's mission statement in DNA: "Empowering each person to store more!" Flash forward to 2024, and Paris-based startup Biomemory has introduced DNA cards, a new form of data storage, priced at $500. Each card offers one kilobyte of storage, equivalent to a short email. This could be useful for anyone wanting to save ultrasensitive data. DNA storage is recognized for its remarkable longevity, with a potential lifespan of hundreds of thousands of years in optimal conditions, far exceeding traditional storage devices like hard drives. (Biomemory's DNA cards guarantee a minimum lifespan of 150 years.) This innovative storage method involves converting digital data into DNA sequences made of the ACTGs (adenine, cytosine, guanine, and thymine) you learned about in high school. The process, which takes about eight hours for 1 kilobyte, involves chemically synthesizing a unique DNA strand to match the desired sequence, then drying and sealing it on a chip to protect against oxygen. To access the stored data, customers must send one of their DNA cards to Biomemory's partner, US-based Eurofins Genomics. The retrieved data, in the form of DNA sequences, is then emailed back and can be decoded using Biomemory's DNA translation feature. Cards aren't rewritable—meaning, they can only be decoded once.

The Intelligence Advanced Research Projects Activity, a group in the Office of the Director of National Intelligence, intends to store an exabyte of data—roughly a million terabyte-size hard drives—in a blob of DNA. A weird branch of biological science, yes, but human computing has practical purposes: DNA could solve our future data storage problems. It's durable, too: Evolutionary scientists routinely study DNA that is thousands of years old to learn more about our human ancestors. In China, scientists at Tianjin University stored 445 kilobytes of data in an E. coli cell. In the US, Twist Bioscience is making hyperdense, stable, affordable DNA storage by using robots to create a million short strands of DNA at a time from microscopic drops of nucleotides on silicon chips. The end result will be a tiny, pill-size container that could someday hold hundreds of terabytes of capacity. Now, a consortium called the DNA Data Storage Alliance is developing an interoperable storage ecosystem using DNA as a data storage medium. Founders include Microsoft, as well as Western Digital, Twist Bioscience, and Illumina. Members of the Alliance, including Los Alamos National Laboratory, Seagate, FujiFilm, Dell Technologies, Lenovo, IBM, and the University of Arizona's Center for Applied Nanobioscience and Medicine are hoping to write megabytes of data per second on synthetic DNA that will be readable for thousands of years.

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Biological Robots

In 2020, a cluster of stem cells from an African clawed frog served as the base for a fortuitous experiment involving a supercomputer, a virtual environment, and evolutionary algorithms. Researchers created 100 generations of prototypes before they had a tiny blob of programmable tissue called a xenobot. These living robots can undulate, swim, and walk. They work collaboratively and can even self-heal. And they're tiny enough to be injected into human bodies, travel around, and—maybe someday—deliver targeted medicines. While technically they're made up of living cells, researchers are quick to point out that xenobots lack the characteristics of a traditional biological life-form. In 2021, xenobots got a design upgrade and new capabilities. While before they needed the contraction of heart muscle cells to move forward, upgraded xenobots can self-propel using tiny hairs on their surfaces. The current crop of xenobots live longer, and they can sense what's in their environment. They can also operate in robot swarms to complete a collaborative task. Xenobots are being used to help researchers understand how defects in the hairlike structures in our lungs, called cilia, can result in diseases. Also in progress: xenobots that can travel to a damaged spinal cord and repair it with regenerative compounds.

Meanwhile, another type of living robot, anthrobots, were developed in 2022 from donated human tracheal cells. Covered in cilia, these anthrobots harnessed the structures like flexible oars to propel themselves around. When grown in a petri dish, scientists discovered the bots could be assembled into super-anthrobots to perform tasks. A team at Tufts University grew a sheet of human neural cells and scratched a few off, to create a defect roughly a millimeter wide. With super-anthrobots on the other side, bots catalyzed healing. While some skeptics claim that the significance of biological robots are overhyped—they're not really programmable robots after all—it's useful to think about this tissue in a broader context. Instead of viewing the cell clusters merely as tiny tissue samples for studying human biology, they have distinct shapes and behaviors that don't already exist in natural organisms. These characteristics will someday enable their use as a biorobotics platform for various medical and other purposes. For example, with some modifications, it's possible to build cell clusters that could be dispatched to repair damaged tissues within the body.

Living Sensors

Research is already underway to develop biosensors that can detect deadly bioweapons on the battlefield and harmful chemicals in factories by identifying the presence of specific DNA sequences. Researchers at the University of California San Diego created a bacterium called Acinetobacter baylyi capable of detecting a single DNA letter mutation in a gene that's present in many cancers. With a focus on the microbiome, they engineered the bacterium to detect mutated DNA sequences while living inside of the gut. While still very early in development, living sensors could someday be used to detect viral outbreaks in a community's sewage system, cholera in drinking water, and other pathogens.

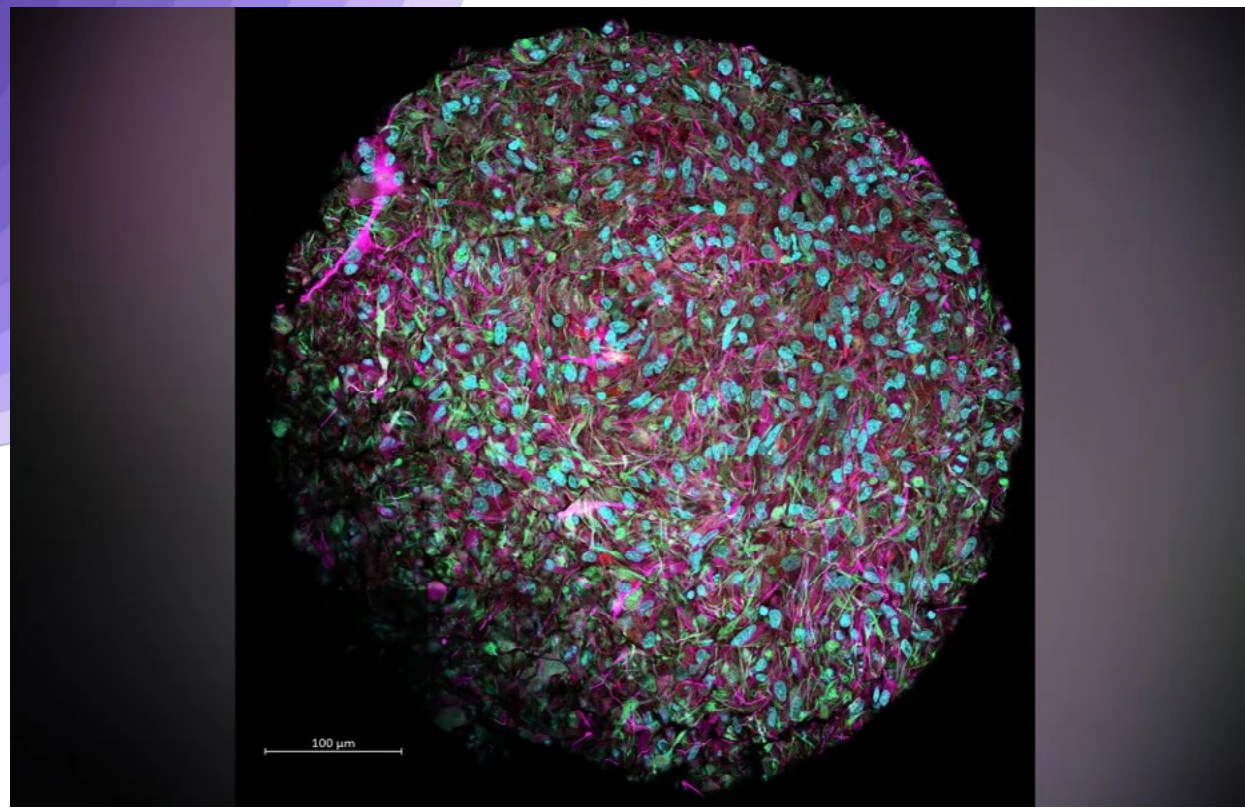
General DNA integrated circuits can solve math problems and identify molecular biomarkers, showing promise that DNA computers might one day prove useful for clinical and diagnostic applications.

Image credit: Future Today Institute and Dall-E.

BIOCOMPUTING AND CYBERBIOSECURITY

Cyberbiosecurity

Cyberbiosecurity is a relatively new intersection between biology, biosecurity, and cybersecurity that will soon become a critical frontier in the safeguarding of the global bioeconomy against burgeoning threats. As AI continues to mesh with life sciences, advancements underscore a dual-edge potential: On the one hand, we'll see faster development of new vaccines, therapeutics, and materials, which stand to promote economic growth while improving health and creating more options to battle climate change. On the other hand, these new tools could be misused. Technologies with AI-bio capabilities bear the risk of triggering biological catastrophes. As of now, there is no single body charged with overseeing cyberbiosecurity. The Nuclear Threat Initiative, a nonpartisan global security organization focused on reducing nuclear and biological threats imperiling humanity, convened a panel of leading experts on synthetic biology, machine learning, bioinformatics, and international security policy in January 2024, however there is no formal governing organization yet. (If this sounds somewhat familiar, it's because it happened before with AI. More than two decades ago, there were calls to establish a similar governing organization for AI. Today, the regulatory landscape is a mishmash of different policies often in conflict and hard to enforce.)



This magnified image shows a brain organoid produced in the lab of Dr. Thomas Hartung, a professor of environmental health and engineering at the Johns Hopkins Bloomberg School of Public Health and Whiting School of Engineering in Baltimore. The culture was dyed to show neurons in magenta, cell nuclei in blue and other supporting cells in red and green.

Image credit: Courtesy Jesse Plotkin and Johns Hopkins University.

NEW MATERIALS

NEW MATERIALS

AI-Created New Materials

Last year, the Google DeepMind team revealed its Graphical Networks for Material Exploration (GNoME)—a sort of AlphaFold, but for new materials. Remarkably, it predicted the structures of 2.2 million new materials, and some 700 have already been created in labs for testing. GNoME has significantly expanded the repository of stable materials to 421,000, a nearly tenfold increase, showcasing its efficiency in identifying viable new materials. Here's why this is significant: the traditional methods used to discover new materials involve experimenting with element combinations from the periodic table, a slow, tedious, and inefficient process. DeepMind uses two deep-learning models instead: the first generates structures by tweaking existing materials, while the second predicts material stability based purely on chemical formulas. This dual-model strategy broadens the search for new materials. GNoME's role is to evaluate these candidates, focusing on their decomposition energy to determine material stability, a crucial factor for engineering applications. Newly discovered materials can be used to make better solar cells, batteries, computer chips, and more. Meanwhile the Lawrence Berkeley National Laboratory created a new autonomous lab using GNoME called A-Lab. It uses a materials database, incorporates findings from GNoME, and employs machine learning along with robotic arms to create new materials autonomously, without human intervention. A-Lab was able to synthesize 41 out of 58 proposed compounds over 17 days, showcasing a much faster pace of material creation compared to traditional labs. This efficiency is critical in a field where experimentation can otherwise be dauntingly slow. AI will significantly enhance the process of discovering and creating new materials, which will ultimately lead to better solar cells, batteries, computer chips, and more.

Modifying Fungi for Building and Packaging

In an era marked by escalating fire risks to residential structures, synthetic biology may help enhance the safety of buildings. Ultra-thin sheets can be made from the expansive, root-like networks beneath mushrooms known as mycelium—and they may be a scalable, novel solution for fire retardation within building materials. Researchers at RMIT University in Melbourne, Australia, have used this technology to develop a new biological material for fire retardancy. Unlike asbestos, which has terrific fire retardant properties but releases harmful particles upon combustion, engineered mycelium are safe and effective. Fire retardant sheets are grown and then layered into protective mats only a few millimeters thick. This innovative fabrication process results in a material that not only delays the ignition of building components, but also exhibits a unique fire response mechanism. In case of a fire, the mycelium sheets momentarily ignite, discharging water vapor and carbon dioxide, thereby reducing the oxygen available for the fire to sustain itself. This reaction culminates in the formation of a carbonaceous layer, which effectively stops the propagation of flames. New York–based Ecovative is also harnessing fungi in its Mushroom Packaging, using organic waste and mycelium grown in custom molds without light, water, or chemicals. This process takes five to seven days and results in a durable, lightweight material that is heat-treated to halt growth, yielding a completely natural and compostable packaging solution. It's an eco-friendly alternative to conventional styrofoam or bubble packaging.

Mycelium Leathers

Besides fire retardancy and packaging, luxury companies are eying mycelium as an alternative to leather. Hermès created a mycelium version of its classic luxury Victoria bag, while Adidas launched a pair of Stan Smith shoes made out of the leather alternative. Bolt Threads and Ginkgo Bioworks announced a multi-project collaboration to optimize the production efficiency of mycelium leathers and to develop novel proteins for biomaterials. Research and Markets, a provider of data and analysis, forecasts that the global market for synthetic leather materials could approach $67 billion by 2030. Meanwhile, the market for bio-based leather, which comprises materials of natural origin, was valued at approximately $650 million in 2021, according to Polaris Market Research. Until now, there have been many leather alternatives made from plastics such

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as polyurethane or polyvinyl chloride, commonly referred to as PVC, leading to the somewhat disparaging nickname "pleather." Mycelium offers a viable, sustainable alternative.

Biomolecule-Based Packaging

Packaging made from natural materials like plants or proteins is biodegradable and safe for the environment. However, single-material packages can have drawbacks, so researchers are mixing different natural substances to make stronger, better packaging. Depending on the food and storage method, these eco-friendly packages can protect food by keeping out germs, preventing spoilage, and reducing water loss, among other things. There's also a new type of packaging that includes natural preservatives to keep food fresh longer by stopping bacteria growth or preventing the food from going bad. Another innovative idea in development is "smart" packaging that changes color or shows signs to indicate how fresh the food is, helping everyone from producers to consumers keep track of food quality.

Intelligent and Active Packaging

Active packaging works by incorporating substances like antimicrobials and antioxidants directly into the packaging to extend the food's shelf life and enhance its safety and taste. For example, a company might use packaging with built-in antimicrobials to keep bread fresher for longer by preventing mold growth. Intelligent packaging, on the other hand, includes smart indicators that show changes in the food's condition, such as freshness, quality, or safety. These indicators can react to environmental changes like temperature, humidity, or the presence of certain gasses. Researchers at the NOVA School of Science and Technology in Portugal are developing bio-based sensors made from natural extracts and biopolymers that can act as smart food packaging, with indicators showing various factors such as freshness. Eventually, this could mean the end of expiration dates, which aren't actually connected to whether food is spoiled or fresh. Expect to see meat packaging that changes color if the meat starts to spoil, or a milk carton with a label that shifts color when the product is no longer safe to consume, giving consumers a clear, visual signal about the state of their food.

Biodegradable and Edible Packaging

Smart packaging will drive agricultural advances and investment. Biopolymers such as polysaccharides, proteins, and lipids can be used to fabricate edible films or coatings as packaging. Rather than throwing away your strawberries' packaging, you can eat the wrapping. University of Minnesota researchers are developing polymers that self-destruct or "unzip" when exposed to light, heat, or acid. Saltwater Brewery designed biodegradable and edible plastic rings for six-packs of beer—so sea turtles can eat them rather than get tangled in them. Infarm created a renewable plastic that folds around objects. It uses seaweed-based agar-agar gel to grow microgreens and herbs that don't need water. At the end of 2022, Prince William awarded a $1.2 million Earthshot Prize to Notpla, a startup that uses seaweed to produce naturally biodegradable packaging.

Durable Biofilms

A biofilm is essentially a community of bacteria living together in a structured formation. While biofilms can be beneficial, such as in treating wastewater, they can also cause significant problems, including damaging infrastructure through corrosion and being involved in up to 60% of infectious diseases. Bacteria in biofilms become tougher, harder to remove from surfaces, and more resistant to antibiotics compared to their solitary counterparts. Researchers at the University of Rochester have developed a method to create biofilms through 3D printing. They've genetically modified bacteria to produce biofilm components, allowing these bacteria to be printed in a hydrogel. This process forms biofilms with a dense network that mimics natural biofilms' structure. The technique offers precise control over the bacteria's distribution and density, enabling detailed studies on biofilm behavior and the creation of biofilms with specific patterns for various applications, opening up a wide array of practical applications in manufacturing, supply chain, transportation, food and beverage, and beyond.

CULTURED FOOD & DRINKS AND NEXT-GEN AGRICULTURE

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Lab-Grown Meat Is Going Mainstream

There is growing interest in cultivated meat, which is produced from animal cells in a lab or biomanufacturing plant, which offers an environmentally friendly (and, let's face it, animal-friendly) alternative to traditional meat production. Concerns about food security underline this push into bloodless meat cultivation. Late in 2020, Singapore approved a competitor to the slaughterhouse by allowing a bioreactor—a high-tech vat for growing organisms—run by a US company to produce cultured chicken nuggets for its residents. The company, Eat Just, manufactured chicken in bioreactors using cells taken from healthy, live chickens. In 2023, the company opened a 30,000-square-foot facility in Singapore, and its bioreactors now have the capacity to produce tens of thousands of pounds of slaughter-free meat. By 2030, Eat Just plans for cultured meat products to cost at or lower the current price points for chicken, beef, and pork. Its successful entry into Singapore, a highly regulated country that's also one of the world's most important innovation hotspots, is accelerating interest in cultured meat's startup ecosystem. Israel is a global leader in the cultured meat sector, with groups like Aleph Farms, which got regulatory approval to sell cultured steaks, and Steakholder Foods, which teamed up with Singapore-based Umami Meats to produce fish filets without contributing to the overfishing of declining fish stocks. On the infrastructure side, Turkey-based Biftek is working on new technologies and serums to reduce the cost of lab-grown meat, and in Mexico, Micro Meat creates technologies to scale up production. In Israel, MeaTech uses 3D printing to produce whole cuts of cell-based meat, while Israel-based SuperMeat has developed what it calls a "crispy cultured chicken." Several startups are bringing cultured meat to market. Finless Foods, based in California, is developing cultured bluefin tuna meat, from the sought-after species now threatened by long-standing overfishing. Other companies, including Mosa Meat (in the Netherlands) and Upside Foods (in California, formerly known as Memphis Meats) are cultivating meats in factory-scale labs. Unlike the existing plant-based protein meat alternatives developed by Beyond Meat and Impossible Foods, cell-based meat cultivation results in muscle tissue that is molecularly identical to animals grown for our consumption—and in some cases, improved. Lab-grown meat also doesn't require the hormones and antibiotics used at conventional facilities.

Synthetic Milk and Cheese

Synthetic milk is coming. It's a promising substitute for cow's milk, offering a similar taste, look, and texture that plant-based options like oat, nut, and soy milks don't match. Hailed as the milk of the future, synthetic milk is considered an eco-friendly choice that could disrupt the dairy sector and potentially disadvantage small-scale dairy farmers. Synthetic cow's milk is cultivated by artificially reproducing the proteins in casein and whey. Casein genes are added to yeast and other microflora to produce proteins, which are purified and transformed using plant-based fats and sugars. Perfect Day makes lab-grown dairy products—yogurt, cheese, and ice cream—that are now sold in thousands of US grocery stores. Remilk, an Israeli company, has established a large-scale production facility in Denmark dedicated to manufacturing cheese, yogurt, and ice cream. Nestle and Danone, two of the world's largest food and beverage corporations, have been on an acquisition spree, buying lab-grown dairy startups around the world. In the next few years, the focus will be on scaling cultured dairy operations and lowering costs of production. New Culture, which makes animal-free cheeses for pizza that stretch, melt, and of course, taste like what you'd find at your favorite local restaurant, upgraded its fermentation process last year. It can produce 25,000 pizzas' worth of cheese in a single run.

Precision Fermentation

Precision fermentation is an advanced version of a very old technology: brewing. For hundreds of years, it's been used to multiply microbes to create specific products, from beers to medicines. Today, precision fermentation can be used for a host of purposes. Food technologists can use genome sequencing and gene editing as part of a precision fermentation process, which results in microbes engineered

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for specific purposes. For example, feeding engineered microbes into a precisely tuned fermenter could create synthetic coconut oil or palm oil. Genetically altered microbes, which are already in use to produce plant-based meat substitutes, could soon form the basis for non-dairy cheeses. With more consumers seeking out vegan options and climate change impacting dairy production, Nestle, Danone, Mars, General Mills, and Unilever are developing precision fermentation platforms to meet future supply chain constraints and market needs. Precision fermentation can also produce new forms of stabilizers and preservatives.

Brewing Great Nonalcoholic Beers

People are becoming more interested in healthier, more responsible ways of drinking, leading to a big increase in nonalcoholic beers. But anyone who's tried a nonalcoholic beer will be quick to complain that it doesn't taste or smell as good as beer fermented the traditional way: The beers typically lack the pungent, hoppy smell and can leave an odd aftertaste. The reason has to do with how they are made. Brewers either stop the brewing process early to avoid creating alcohol, or they let the beer ferment and then remove the alcohol. Both methods tend to remove the hop aromas, which are important for making beer smell good. But biotech startup EvodiaBio seems to have found a solution. Its scientists developed a method to create monoterpenoids, the compounds responsible for the hoppy flavor, and add them to beer after brewing, restoring the flavor that usually gets lost. By using baker's yeast cells as tiny biofactories, the team can generate these hop aromas in fermenters, avoiding the waste of expensive hops that typically lose their flavor during the brewing process. This approach not only enhances the taste of nonalcoholic beer but is also much more eco-friendly compared to using traditional hops. For example, in the US, aroma hop farming happens mainly on the West Coast—which means that anyone outside the area must rely on an extensive transportation and refrigeration cold chain, not to mention the considerable amount of water needed for cultivation (about 2.7 tons of water to produce just 1 kilogram of hops).

Upgrading Photosynthesis

Genetically modifying crops with upgrades could dramatically increase crop yields without needing to increase the other resources required for cultivation. Researchers are working on a number of projects that would increase photosynthesis—the biological process green plants and some organisms use to harness sunlight to produce energy out of CO2 and water. Simply over-exposing plants to sunlight doesn't have the same effect—more light can damage cells unless they turn on a biological system called quenching that's capable of flushing out the excess energy. On cloudy days, plans turn off quenching to retain the excess energy, but the process of turning quenching on and off is time-consuming, unpredictable, and inefficient. Scientists hope that with genetic engineering, they can speed up the quenching process, which would lead to more efficient photosynthesis. In 2022, modified soybean plants were shown to yield 20% more thanks to a jacked-up photosynthesis system. Researchers are also working on cowpeas and rice.

Bioluminescent Firefly petunias give off an eerie glow in the dark.

Image credit: Light Bio

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Faster Flowering

Using the CRISPR gene-editing tool, researchers at the University of Georgia Warnell School of Forestry and Natural Resources and at Franklin College of Arts and Sciences figured out how to make trees mature faster. They used CRISPR to edit a flower repressor gene and drastically shortened the time it takes a poplar tree to flower—from 10 years down to just three months. It would typically take the plant a year to develop the systems to even produce flowers, and the team engineered the plant to mature in just a few days. The promise of this research is an accelerated time frame for tree breeding, as well as to enhance the natural defenses of trees from extreme heat, cold, and drought.

A Return to Natural Farming—With Technology

Farming faces a big challenge: how to provide plants with nitrogen to feed more people without harming the environment or reducing crop sizes. Nitrogen is essential but expensive, and the usual synthetic fertilizers cause pollution and contribute to climate change. They're also not very reliable because they can easily wash away or evaporate. Healthy soil, full of microbes like bacteria and fungi, naturally supports plant growth by recycling nutrients, but chemicals can harm this balance. Synthetic biology offers a solution. Pivot Bio, a biotech company, has developed a way to enhance a soil microbe's ability to supply nitrogen directly to plants, offering a steady and environmentally friendly source of this crucial nutrient throughout the growing season without genetic modification from other organisms.

Regenerative Agriculture

Regenerative agriculture describes farming and grazing practices that rebuild soil organic matter and restore degraded soil biodiversity. There's a clear need for this technology-led practice: Decades of using chemicals, salt-based fertilizers, carbon mining, and harsh insecticides deplete soil. Planting multiple types of crops together, rotating crops, cutting back on tilling, and reducing reliance on harsh chemicals can revitalize depleted soil, leading to improved yields, nutrient-rich crops, and improved resistance to flooding and drought. In 2017, the Rodale Institute launched the Regenerative Organic Certified program to start creating an official standard. It builds on the USDA certified organic seal by adding soil health, animal welfare, and human rights requirements. General Mills announced that it would accelerate regenerative agriculture by dedicating a million acres of farmland to it by 2030. Meanwhile, several brands, including Patagonia, Timberland, Allbirds, Gucci, and Balenciaga, have launched efforts to promote regenerative agriculture.

A New Wave of Genetically Modified Foods

A recent Pew Research study showed that most Americans see food using genetically modified organisms as worse for their health than a food that has no genetic modification at all, while just 7% see them as healthier than other foods. GMOs have a public perception problem because some of the earliest modified crops (corn and soybeans) were genetically changed to tolerate herbicides like glyphosate, which sells under the brand name Roundup, and last year in the US, 91% of domestic corn production used these herbicide tolerant seeds. So, it's understandable that people are wary of a new crop of GMOs. But the promise of supercharged foods enhanced to produce additional nutrients—rather than modified to respond to a particular fertilizer or pesticide—may change people's minds. Biofortified foods are genetically enhanced to provide a denser dose of nutrients. California-based Fresh Del Monte created a pink pineapple that's been modified to have a higher level of lycopene, an antioxidant that gives peaches, tomatoes, and watermelon their rosy hues. Early in 2024, the Purple Tomato, developed by Norfolk Plant Sciences, was approved to be marketed directly to home gardeners. It was the first time that genetically modified foods were available to noncommercial producers in the US. The tomatoes are bright purple thanks to color genes from a snapdragon flower that were added to the plant. They're not only unusual looking, they have high levels of anthocyanin, which has antidiabetic, anticancer, anti-inflammatory, antimicrobial, and anti-obesity effects and is used to prevent cardiovascular diseases.

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CRISPR Animals

CRISPR is making farmed animals bigger, stronger, and (hopefully) healthier. Researchers at Auburn University in Alabama introduced a gene from alligators into catfish, not aiming to give the catfish alligator characteristics, but rather to boost their ability to resist diseases. This is because alligators are exceptionally good at warding off infections, and a slight increase in resilience could significantly impact fish farming. Currently, about 40% of fish raised in farms globally don't survive until harvest, so reducing even a fraction of this loss could be transformative. Scientists in Japan used CRISPR to modify the myostatin gene in red sea bream, resulting in fish that are larger and heavier by about 17% compared to nonmodified fish, even though both groups were fed the same quantity of food. Researchers have long experimented with CRISPR on animals, and so far have used it to create super-muscly pigs, cattle, sheep, rabbits, and goats. But most animals did not live past infancy, and, somewhat weirdly, many developed unusually large tongues.

Genetically Engineered Space Farming

Growing plants in space, on the moon, and Mars is important for keeping astronauts healthy and happy. NASA has been looking into this for years, focusing on building the right equipment to grow plants, choosing the best types of plants for space nutrition, and studying how plants react to being in space, including how they interact with microbes. Recent advances in gene-editing technology, like CRISPR and other tools, have made it easier to tweak plant genes for space needs. These tools, along with new ways to deliver gene-editing materials to plants and the use of big data and machine learning to analyze plant genes, are opening up possibilities for creating plants that can thrive in space. Looking ahead, experts believe it's crucial to focus on using these technologies to develop plants that meet the specific needs of space missions, making space agriculture more sustainable and effective. Space agriculture is quickly becoming a multibillion-dollar industry. NASA and Germany's space agency are now investing in a variety of space agricultural projects that could someday support off-planet habitats.

Researchers in China created double-muscled pigs by introducing a mutation into the pigs' genetics that keeps the muscles developing beyond the point they would naturally. Note: this image is AI-generated, and does not show a live animal.

Image credit: Future Today Institute and Dall-E.

AGING, HEALTH, AND BEAUTY

AGING, HEALTH, AND BEAUTY

Cultivated Collagen

Israel-based Aleph Farms has already brought cultured steak to market. Their next goal: cell-cultured collagen, which is part of a broader strategy to replace the entire cow. The company is developing a way to produce collagen directly from cow cells, avoiding the need to raise and harvest livestock. Traditionally, collagen is derived by boiling cow hides and bones, a process used across various industries. Aleph Farms will use techniques from its steak production, such as bovine cell sources and a growth medium free of animal components, to create different types of collagen that are identical to those found in nature. This cultivated collagen will include a full range of proteins found in the extracellular matrix, which makes up skin, bones, and joints. There are other startups now working on collagen cultivation, too. Jellatech, a North Carolina–based startup, created a full length, triple helical, bio-identical and functional human collagen made from its proprietary cell line.

Growing Blood

For people who live with rare blood types (AB negative, AB positive, B negative) or who have blood disorders, acquiring blood for surgery or a transfusion can mean the difference between life and death. For decades, scientists have attempted to grow blood cells in a lab at scale, but until recently, the process has failed to produce enough blood cells to make an impact. But late in 2022, scientists at the National Health Service Blood and Transplant in the UK announced that they had grown red blood cells in a lab and successfully transfused them into a living person, a world first. It took 500,000 stem cells to generate 50 billion red blood cells, which then needed to develop. (In a healthy adult, 50 billion red blood cells represents about 1% of their total blood volume.) Last year, the same researchers transfused red blood cells that were grown in a lab into another person requiring that blood. This technique is a pioneer in transferring lab-grown cells to another person as a part of a blood transfusion. Going forward, patients who need regular blood transfusions could go longer between treatments. After that, researchers will set their sights on manufacturing lab-grown blood for rare blood types that don't typically have large donor pools.

Growing Sex Cells

Last year, Dr. Katsuhiko Hayashi from Osaka University successfully created eggs from cells harvested from male mice, with the eventual goal of developing new fertility treatments. The process begins with taking a skin cell from a male mouse and converting it into a stem cell, which has the potential to develop into various cell types. Since these cells are male, they carry XY chromosomes. The team then removes the Y chromosome, replicates the X chromosome, and combines the two X chromosomes—a modification that enables the stem cell to develop into an egg. Hayashi's work builds on groundbreaking research from fellow Japanese scientist Shinya Yamanaka, who in 2006 showed that it was possible to make gametes derived from human-induced pluripotent stem cells. Yamanaka's process includes harvesting cells from a skin biopsy or blood sample (both quick and relatively painless). Those cells are turned into stem cells, grown in a medium that resembles what would exist in a human womb, and developed into precursor sex cells, which mature into sperm or stem cells. Then, once IVF kicks in, those cells are used to create an embryo. One or more of the healthiest embryos are then implanted into the uterus and, if all goes well, develop into a healthy, viable fetus. The idea is that someday soon, couples suffering from infertility or individuals who desire to have a baby without a partner would have access to a reliable fertility treatment.

Human Trials of Synthetic Wombs

Researchers at the Children's Hospital of Philadelphia (CHOP) created an artificial womb called a biobag and used it to successfully keep premature lambs alive and developing normally for 28 days. Now, CHOP researchers are seeking approval to begin the first human clinical trials for a device they've developed, called the EXTra-uterine Environment for Neonatal Development, or EXTEND. The team has clarified that this technology is not designed or capable of supporting the full spectrum of

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development from conception to birth, but is intended to increase survival and improve outcomes for extremely premature babies by replicating a natural womb environment. The FDA is still working with independent advisers to determine regulatory and ethical considerations for synthetic wombs and ethical considerations for what human trials could look like. Other teams around the world are developing similar devices, while bioethicists are working out the broader implications. What if synthetic wombs aren't available to lower-income people? How might they factor into debates over reproductive rights? And what if, further in the future, they eliminate the need for a person to carry a pregnancy at all?

Universal Cancer Vaccines

Early in 2024, the first patient in the UK received a dose of a cancer vaccine as part of a larger clinical trial. Designed to treat solid-state tumor cancers, such as melanoma, this application of immunotherapy harnesses the immune system to fight cancer cells. ("Vaccine" is a bit confusing here, since most vaccines are designed for prevention, while this treatment is for people who have already developed a tumor.) Called mRNA-4359, the treatment contains a molecule that can relay instructions to cells. It works by directing cells to produce proteins typically found on the surface of solid cancer tumors. Once these proteins are made, they are introduced to the immune system, training it to recognize and attack cancer cells.

This vaccine is classified as a "universal" cancer vaccine, meaning it is premade and can be administered to patients with certain types of cancer straight from the shelf. In contrast, other mRNA cancer vaccines being developed are customized based on the individual patient's cancer, such as a pancreatic cancer vaccine that uses genetic material from the patient's own tumors for a more personalized approach.

Long before they were making Covid vaccines, both Moderna and BioNTech were researching immunotherapies for cancer. After analyzing a tissue sample from a cancerous tumor, the companies ran genetic analyses to develop custom mRNA vaccines, which encode protein-containing mutations unique to the tumor. The immune system uses those instructions to search and destroy similar cells throughout the body, which is similar to how the Covid vaccines work. BioNTech is running clinical trials for personalized vaccines for many cancers, including ovarian cancer, breast cancer, and melanoma. Moderna is developing similar cancer vaccines and announced that its personalized cancer vaccine, when combined with Merck & Co.'s immunotherapy treatment Keytruda, cut recurrence and risk of death of the most deadly skin cancer compared with immunotherapy treatment alone. In the trial, the mRNA vaccine revved up the immune response.

Upgrading Embryos Before Birth

Researchers are developing a new technique that might someday enable people to optimize their children's genes before birth. Using algorithms to understand the tiny variations in DNA—single nucleotide polymorphisms, or SNPs—these researchers hope to make accurate gene-based predictions about an individual's future. SNPs are important markers of genomic variants at a single base position in the DNA—and these single letter changes to our genetic code are contributors to conditions like diabetes. If SNPs were read in vitro, before embryos were implanted, they could reveal whether that genetic combination had a higher probability of developing diabetes or even heart disease. If an embryo were edited using CRISPR, embryos could also be optimized with the best possible traits, given the raw genetic material. Theoretically, parents could influence myriad traits for their offspring, including hair texture, resistance to a virus such as HIV, or protection against Alzheimer's disease. This intervention, like the gene drive edit to make mosquitos unable to transmit malaria, would have a permanent, heritable effect. It could eradicate certain diseases passed from parents to children, and in the process improve the entire gene pool.

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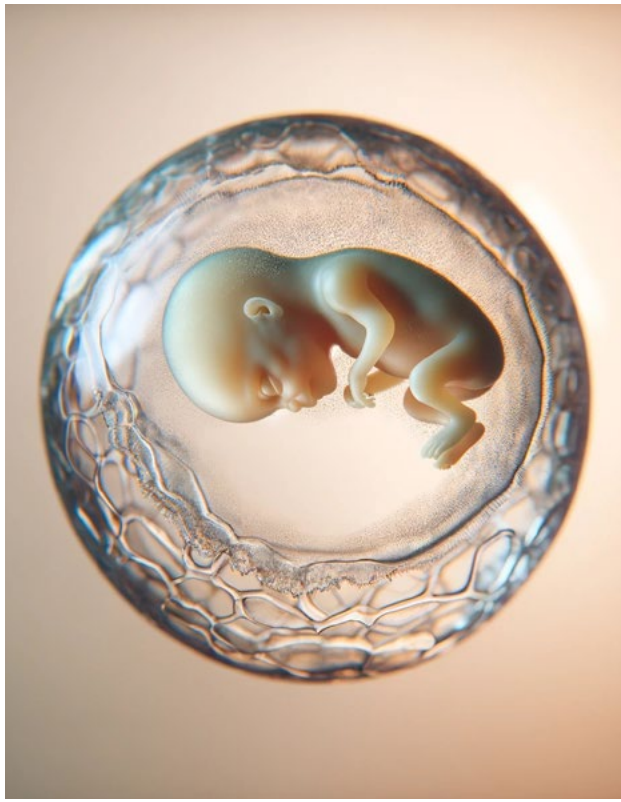
Genetic Screening for Pregnancy

Genetic screening tests promise a kind of prenatal fortune-telling: Many companies say they can predict the health outcomes of growing embryos. California-based MyOme and New Jersey–based LifeView use the genetic sequences of parents, along with cells retrieved during a biopsy, to generate an embryo's entire genome. Next, they use algorithms to calculate the probabilities of certain ailments. Couples going through fertility treatments have a limited number of embryos to choose from and would be able to select the embryos they like based on those results. Other startups offer to calculate scores and optimize for other genetic traits such as height and intelligence. LifeView provides genetic report cards to would-be parents: they deliver a report showing whether the embryo has the right number of chromosomes, risk assessment grades for heart attacks, certain cancers, diabetes and more.

Genetic screening is a booming market in the US—and last year, the FDA moved to regulate prenatal testing. The proposed regulations aim to clarify that the FDA has the authority to regulate the noninvasive prenatal tests developed and used by individual laboratories. These tests have rapidly evolved from niche laboratory trials to a major industry; over a third of pregnant women in the US receive a simple blood test in the first trimester to check for fetal genetic abnormalities. While these tests are highly reliable for detecting common genetic conditions such as Down syndrome, the accuracy of newer tests for rare abnormalities is often questionable, frequently producing incorrect positive results. Such inaccuracies can lead to significant anxiety for expectant parents, sometimes prompting unnecessary and costly follow-up procedures. Under the new FDA oversight, the marketing and availability of such tests would require government approval, especially for tests considered "high risk" because they could influence critical medical decisions.

Biobank Releases

The UK Biobank made 500,000 genome sequences available to scientists for biomedical research projects last year. This extensive collection of sequences offers an invaluable tool for exploring the genetic foundations of human health and various diseases. Labs worldwide have the opportunity to access these data sets, with the UK Biobank having granted approval to over 30,000 researchers from around 90 countries to date. Scientists have published more than 9,000 peer-reviewed studies using Biobank data, investigating genetic influences on a range of conditions and traits, including Alzheimer's risk, heart disease, personality traits, and even sexual orientation—though that last one has sparked debate. Whole genome analysis, unlike exome studies, lets scientists examine associations between traits and rare genetic variations in both the protein-coding and noncoding segments of the genome. While it's understood that noncoding regions play roles in gene regulation among other functions, much about their contribution to human biology remains to be discovered. The expansion of this data set should drive significant breakthroughs in the near future.



Soon, it may be possible to upgrade embryos before birth using new biotechnology techniques.

Image credit: Future Today Institute and Dall-E.

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Microbiome Metrics at Home

The human microbiome is a mini-universe of the genetic materials living on and inside our bodies, inherited from our gestational mothers. It's vast: there are 200 times more genes in the bacteria, fungi, protozoa, and viruses that make up our microbiomes than in the human genome. That microbiome weighs nearly 5 pounds, and it lives mostly in your gut and on your skin. Microbiomes differ greatly from person to person, even if you're comparing siblings who live in the same city. How well you digest lactose, how vulnerable you are to skin cancer, how well you sleep, your probability of developing anxiety or becoming obese—all of these traits are linked to the microbiome and influenced by what you eat and drink, whether you smoke, what chemicals your body comes into contact with, and what medications you take. Data about your microbiome used to be collected over several visits to an allergist, but today, at-home tests can determine its genetic makeup. Some companies will mix together special probiotic compounds to mitigate conditions or optimize the symbiotic relationship your body has with all those microorganisms.

Age Reversal

As we age, while our DNA sequence might stay constant, chemical changes do occur. Observing those changes could lead to new techniques to halt or even reverse age-related disease. Columbia University researchers discovered that it might be possible to record and store information about cells as they age. The technique, a sort of biological DVR, uses the CRISPR-Cas system over a period of days. In the future, if we can quantify aging at a cellular level, we might be able to reverse it. Synthetic biologist George Church and a team at Harvard's Wyss Institute combined three different gene therapies related to cellular decay into a single compound. The intent: reverse obesity and diabetes while also improving kidney and heart function. Remarkably, the technique seemed to work (in mice, at least). Maybe that's why last year there were so many funding and partnership announcements in the field. The Saudi royal family launched the Hevolution Foundation, a not-for-profit with an annual budget of $1 billion to support basic research on the biology of aging. Meanwhile, the startup Altos Labs is developing biological reprogramming technology. In 2022, Altos, which raised a staggering $3 billion in funding over just one round, announced a partnership with the Center for iPS Cell Research and Application at Japan's Kyoto University to study cellular rejuvenation programming.

Removing Zombie Cells

Senescent cells are damaged cells that stop functioning but don't die, accumulating in the body like cellular zombies—and they're linked to aging. But scientists are researching the use of senolytic drugs, which remove these worn-out immune cells, as a way to treat diseases like multiple sclerosis. In MS, the immune system attacks the myelin sheath around nerves, and while it's characterized by phases of relapse and recovery, it can eventually progress into a phase where symptoms continuously worsen without periods of remission. In older animals, myelin damage leads to lots of senescent cells. But when researchers at Georgetown University injected older mice with a toxin to damage myelin and then treated some with senolytic drugs, the treated mice showed a 65% greater increase in a myelin-rebuilding protein compared to untreated mice. This finding indicates that removing senescent cells could improve myelin repair, and could mean that senolytic drugs offer a new treatment strategy for MS, particularly in its progressive stage—if it works in humans as well as it does mice, which for now is a big if. But if human trials show promising results, it is plausible that senolytic drugs could be developed to treat a host of diseases and ailments, along with conditions associated with aging.

Skin Care and Beauty

Synthetic biology–derived compounds are producing improved ingredients in skin care products. Amyris, one of the first commercial synthetic biology companies, created a suite of products developed with biosynthesis to create squalene, a key antioxidant found in moisturizers. Bay Area startup Geltor is engineering animal-free collagen for use in serums and creams, designed to plump skin and reduce the appearance of fine lines and wrinkles. Conventional collagen is usual-

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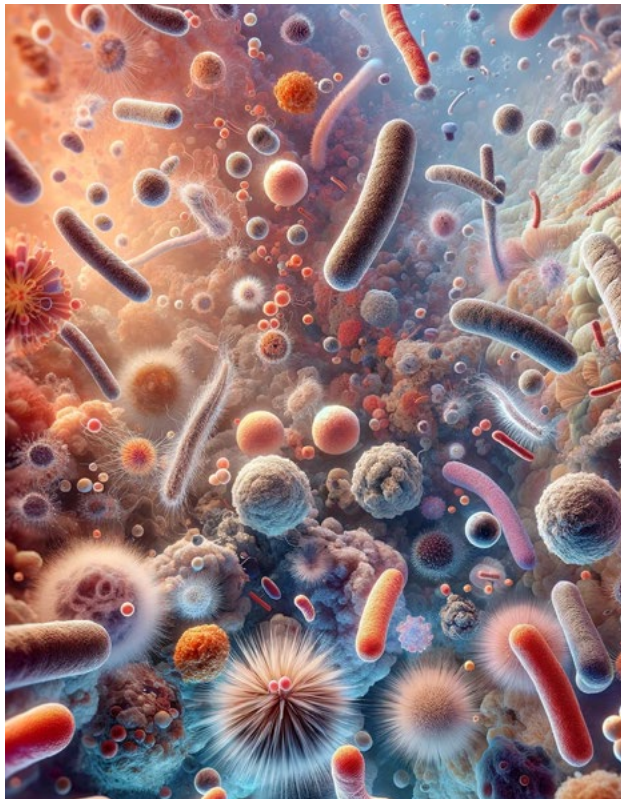
ly drawn from bovine sources, but modern bioengineering means it can be grown in a lab. Skin care brand Algenist uses bio-fermented microalgae in its antiaging products, and it developed alguronic acid that makes skin look more youthful. One Ocean Beauty, founded by former Burberry Beauty President Marcella Cacci, produces a bio-fermented exopolysaccharide isolated from brown kelp, an elasticity-promoting glycoprotein, and a blue light-repellant microorganism—all from cells found naturally in the ocean.

Improving Gut Biomes

A mass extinction event is happening right now in our guts and in the environment. The widespread use of antibiotics, along with diets rich in processed foods, have led to a staggering decline of microorganisms inside the people and animals living in wealthy nations. During the past 12,000 years of human evolution, we've shifted nature's balance—our diets are now relatively narrow, compared to our far-distant ancestors. Recently, scientists studied modern hunter-gatherer tribes in Tanzania, Peru, and Venezuela, and found their microbiota had 50% more bacterial species than those in the West today. Unlike those tribes, we no longer hunt and eat wild flora and fauna. Those from wealthier countries now eat very little dietary fiber, a limited variety of fruits and vegetables, and only four species of livestock: sheep, poultry, cattle, and pigs. Worse, widespread use of antibiotics in farm animals—used not necessarily to prevent disease but to increase weight gain and therefore the volume of meat available—means that we're ingesting compounds that are helping to destroy our own microbiomes. Humans are complex, composite organisms, made up of layers and layers of cells. Researchers now think that our gut microbiome is directly linked to our metabolism, our immune systems, our central nervous systems, and even the cognitive functions inside our brains. It's an inherited problem: Most of our microbiomes come to us from our mothers as we pass through the birth canal. A number of researchers are now looking at the future of our microbiomes. Vedanta Biosciences is making gut bacteria that can be turned into drugs and counts the Bill & Melinda Gates Foundation as one of its investors. The American Gastroenterological Association and OpenBiome will track 4,000 patients over 10 years to learn about fecal microbiomes.

Optimizing Recreational Drugs

When it comes to recreational drugs like marijuana, genetic factors can determine whether someone feels pleasantly relaxed or anxious and listless. New diagnostic tests promise to optimize recreational drugs for someone's unique genetic profile. Atai Life Sciences NV, based in Berlin, is researching genetics, depression, and small molecules within cells in an effort to repurpose psychedelics as therapies for depression and PTSD. MindMed in New York is developing a platform to help patients determine which drugs to take—therapeutics based on MDMA and DMT—depending on genetics and other data.



Scientists are learning more every day about the relationship between our gut microbes and our bodies.

Image credit: Future Today Institute and Dall-E.

CLIMATE AND SUSTAINABILITY

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eDNA Detection

Environmental DNA, or eDNA, is genetic material found in the environment. Feces and fur from animals, as well as hair and saliva from humans are just some of the organic matter found in soil, seawater, snow, and air. As a fish moves through water, it's continuously shedding bits of itself. Likewise, when a cyclist rides on a trail, her sweat, mucus, and dead skin cells wind up mixed into the gravel and dirt. These fragments of nuclear or mitochondrial DNA can reveal invaluable insights about an environment. Scientists from the United States Geological Survey and the Monterey Bay Aquarium Research Institute are developing a new mobile eDNA sampler that can float through rivers and streams, collecting material and detecting pathogens or invasive species autonomously. As detection systems advance, eDNA detection will serve as early warning systems for potential outbreaks. But there's another interesting use for eDNA: reconstructing ancient ecosystems. Scientists excavated eDNA from frozen soil in the Arctic desert, and were able to piece together a lost world nearly 2 million years old. The eDNA revealed a coastal forest with conifers, black geese, horseshoe crabs, lemmings, and mastodons—a natural wonderland unlike any in existence today.

Using CRISPR for Sustainable Wood Production

Trees are a valuable natural resource, but improving their wood through traditional breeding is slow and complicated due to their complex genetics. CRISPR technology offers a way to quickly change trees to improve their wood—optimizing it for paper-making or reduced carbon emissions, for example. Scientists have used CRISPR to change multiple genes in poplar trees, resulting in wood that's easier to process and better for the environment. This breakthrough means we can now grow trees that are more suited for our needs while also helping the planet. The key challenge has been dealing with lignin, a natural part of wood that's tough to break down. But by precisely editing genes related to lignin, researchers at North Carolina State University have created poplar trees with wood that's much easier to turn into fiber. These advancements could make forestry more sustainable and efficient, offering new economic and environmental benefits.

Better Plastics Recycling

Despite global efforts to recycle plastic products, there are numerous barriers: Consumer-facing plastics come in different varieties, they're often coated with labels or print, and they have colors and other added features. The mess of waste—used iPhone cases, empty shampoo containers, soda bottles—can't be easily managed at scale, so a lot of it piles up. A potential solution is microorganisms like some bacteria and fungi that use special enzymes to break down various types of plastics. But turning plastic into something these microbes can eat isn't as simple as just mixing them together. The plastics need to be pre-damaged by sunlight or chemicals, and the microbes need just the right conditions to do their work. Even so, each type of microbe can only eat certain plastics, and it can take them weeks or months to break down just a small amount.

Now, an emerging synthetic biology process offers a new solution. France-based Carbios developed a process using an enzyme that's especially good at breaking down PET plastic into its basic building blocks, making it possible to recycle PET into high-quality new plastic. After improving the enzyme and testing it in an industrial setting, Carbios is now building its first site dedicated to this bio-recycling process. Meanwhile, researchers at SLAC National Accelerator Laboratory and the National Renewable Energy Laboratory used a microporous material called a zeolite that contains cobalt nanoparticles as a catalyst to break down different polymer molecules, turning the majority into propane. At the University of Texas at Austin, researchers used a machine learning model to generate novel mutations to natural enzymes that allow bacteria to break down the plastics found in soda bottles and most consumer packaging. The enzyme, called FAST-PETase (functional, active, stable, and tolerant PETase), could operate efficiently and work at an industrial scale. The first real-world application: setting the enzyme loose to clean up landfills.

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Engineering Plants for Carbon Capture

Carbon dioxide is the undisputed culprit when it comes to climate change. But what if we could just suck it out of the air? Trees do that naturally, but with deforestation, there's not enough to make a sizable impact. The Salk Institute's Harnessing Plants Initiative is working on an innovative approach that relies on our existing carbon storage mechanisms to help solve climate change. It's developing engineered crops that can store more carbon in the ground for long periods of time. The crops have a larger root mass, are deeper, and contain more suberin, a plant tissue that already relies on CO2 and can store significant amounts without causing harm to the plant. Salk researchers are hoping to develop strains of rice, wheat, corn, and other plants that both produce edible crops and store carbon, for improved soil health. Meanwhile, an artificial leaf developed at Harvard harnesses solar energy. When connected to a strain of bacteria, it converts atmospheric CO2 and nitrogen into organic forms that can benefit living organisms. Those hungry, solar-fed bacteria essentially overeat, to the point where 30% of their body weight is excess energy—stored CO2 and nitrogen. These microbes then get mixed into soil, and release all that nitrogen near the roots of plants, acting as an organic fertilizer. At that point, they also release the CO2, yet it remains trapped underground. The result: enormous crop yields without the environmentally poisonous side effects typically associated with chemical fertilizers.

Greening Fashion

The textile and clothing industry is a notorious polluter but is making steps toward more sustainable practices. Fuzhong Zhang, a professor at Washington University in St. Louis, has advanced the production of synthetic spider silk, which could lead to sustainable clothing manufacturing. Using synthetic biology, his team created a process to yield more silk from microbes, aiming to meet the fashion industry's demand for renewable materials and reduce the environmental impact associated with clothing production. By incorporating a protein from a common shellfish—mussels—the team developed silks that are stronger, tougher, and lighter than previous versions, with an eightfold increase in yield. This innovation could provide an eco-friendly alternative to traditional textiles, drastically reducing waste in the fashion industry. The engineered silk, combining mussel foot proteins with spider silk properties, has already reached production levels sufficient for real-world product testing, marking a significant step toward its commercial use. Already, several other successful trials of synthesized textiles have occurred: Bolt Threads developed a synthetic fabric called Microsilk that's engineered from spider DNA, and Japanese startup Spiber synthesized enough fibers to manufacture a limited-edition parka. While manufacturing new textiles is on the horizon, getting bio-sourced materials such as PHAs, spider silk, and chitosan into the supply chain process remains a challenge. Mills and manufacturers don't have incentives to risk using new materials that may not work seamlessly with their existing production equipment.

The Salk Institute's Harnessing Plants Initiative is working on an innovative approach that relies on our existing carbon storage mechanisms to help solve climate change.

Image credit: Salk Institute.

CLIMATE AND SUSTAINABILITY

De-Extincting Lost Species

Woolly mammoths were once a "keystone species," one that other species in the ecosystem depended on in many ways for stability. They stomped around in herds, knocking down trees and packing down snow layers as they searched for dead grasses to eat, and that helped keep the permafrost layer stable. Once the mammoths and other large grazing animals stopped compacting the snow and eating dead grasses, the ecosystem began to change: The snow melted more easily, which allowed the sun to reach the permafrost. The permafrost layer is now melting at an alarming rate and releasing greenhouse gasses into the atmosphere, which creates a vicious cycle: Hotter temperatures lead to more melting, which releases more gasses, which causes hotter temperatures, and on and on it goes. Researchers are helping to de-extinct the woolly mammoth and other species using synthetic biology techniques: Starting with a fully intact healthy cell from a closely related species and working backward, with genetic fragments from preserved specimens, they could develop a version of the animals that once existed.

Rewilding Barren Terrains

Rewilding is a direct human intervention into nature using technology and science, a holistic approach to conservation that focuses on restoring the natural phenomena of wilderness ecosystems, providing connective corridors between wild spaces, and reintroducing keystone species to their natural habitats. A term coined more than 30 years ago, "rewilding" has gained renewed attention in the past few years as the climate crisis has grown more dire and new technologies have promised to protect and rehabilitate ecosystems. In 2017, researchers plunged into the waters off Lizard Island on the northeastern coast of Australia with some unexpected equipment in tow—a set of underwater loudspeakers. Their destination was a coral reef that had been all but abandoned by a once-thriving population of sea life. The researchers hoped that by broadcasting the telltale sounds of a healthy reef, they might lure back some of its vital inhabitants. Remarkably, it worked. This experiment was a unique instance of rewilding, but there have been others. In 2022, four bison were released in a woodland near Canterbury—the hope is that over time, the herbivores will revitalize a stretch of southeast England and allow vegetation to grow again, which should in turn boost biodiversity.

CRISPR Mosquitoes

Gene-drive technology, which has the potential to spread antimalarial genes among mosquito populations, is showing promise. Malaria kills hundreds of thousands of people every year; 96% of the deaths are in African countries, and particularly impact children under age 5. The idea of gene drive, which uses special DNA pieces that copy themselves and spread quickly through an organism's genes, was thought of years ago. However, it had problems because these DNA pieces could end up in important parts of the genes and cause harm. CRISPR-Cas9 technology, which allows for precise genetic edits, enables the safe transfer of antimalarial genes from one generation of mosquitos to the next. This advancement offers hope for controlling malaria by genetically modifying mosquitoes to resist or eliminate the disease. There have now been several pilots around the world to edit mosquitoes so they no longer carry malaria. In 2021, biotech company Oxitec launched a controversial field test of specially engineered mosquitoes in Florida in a move toward reducing the spread of deadly diseases such as dengue, yellow fever, and the Zika virus. Its tiny capsules contain an engineered form of the Aedes aegypti mosquito, called OX5034. Because only female Aedes aegypti bite and spread disease, Oxitec engineered males to pass on a gene that kills female offspring before they mature. Male offspring then continue mating and passing on the altered gene, which should change the population of disease-carrying mosquitoes. The US Environmental Protection Agency said this pilot poses no human threat, while local authorities, who have been dealing with steadily growing cases of dengue fever and West Nile virus, hope that a smaller mosquito population will curb the diseases without insecticides or poisonous chemicals. The EPA later approved an expanded plan to release 2.4 million genetically engineered mosquitoes in more US sites, including California. Similar

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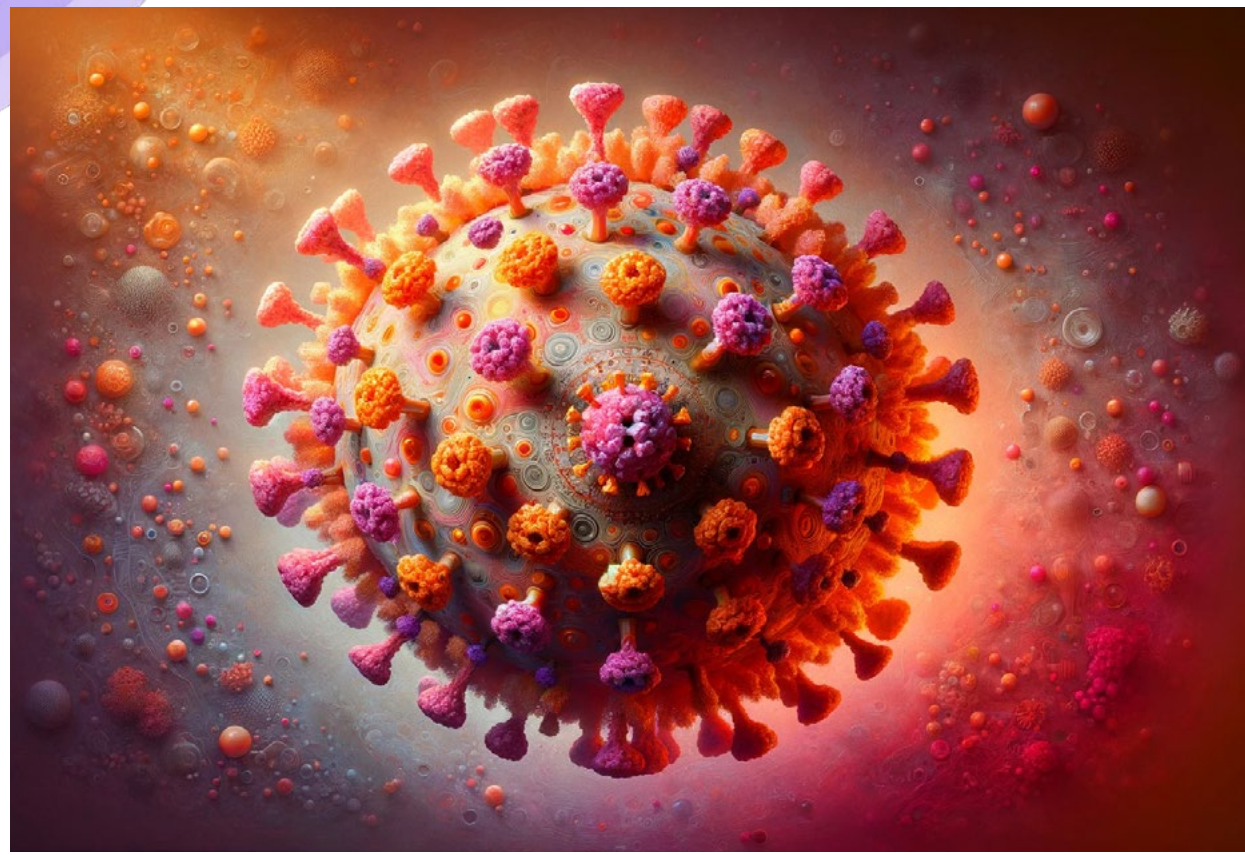
experiments are underway in Malaysia and Panama. While they can transmit malaria, researchers are also thinking about how to use engineered mosquitoes to deliver a defense against deadly viruses. What if in the future mosquitoes are flying syringes capable of delivering vaccines? University of Washington scientists are working on a weakened form of malaria-causing Plasmodium parasites that won't get people sick but will cause the body to create antibodies. On the other hand, could meddling in the genetic code of insects, reptiles, and animals have catastrophic consequences that no one anticipates? If that sounds familiar, it's because you've seen that movie before: "Jurassic Park."

Reviving Ancient Viruses

As the Arctic warms, the thawing permafrost is raising concerns about the release of ancient viruses that could pose health risks to animals and humans. Scientists highlight the potential danger of these long-dormant viruses, along with the release of chemical and radioactive waste from the Cold War era, emphasizing the importance of keeping permafrost frozen. The permafrost acts as a natural time capsule, preserving not only viruses but also extinct animals, which scientists have been able to study. The rapid warming of the Arctic threatens to disrupt this frozen archive, with temperatures there rising up to four times faster than the global average. Research into "zombie viruses" found in Siberian permafrost has shown that some of these viruses are still infectious, which could mean a potential future risk of outbreaks from ancient pathogens. Global warming and increased activity in the region could heighten the possibility of a spillover event. Scientists advocate for proactive surveillance and research to understand the risks posed by thawing permafrost and to mitigate the impact of climate change on the release of pathogens.



As the permafrost layer melts, ancient viruses could thaw and release pathogens harmful to the modern world.

Image credit: Image credit: Future Today Institute and Dall-E.

REGULATION AND POLICY

REGULATION AND POLICY

Regulatory Changes Toward Genome-Edited Crops

Starting last year, countries have been reevaluating their regulatory stance on genome-edited crops, marking a significant change in agricultural biotechnology policies. China's recent safety assessment guidelines for these crops show a partial shift from traditional regulations on genetically modified organisms, signaling a move toward a more nuanced approach that seeks to balance scientific innovation with public trust. Last July, the European Commission proposed legislative changes to relax the rules on gene editing, suggesting a departure from stringent GMO laws for certain next-generation techniques. This proposed legislation argues that edits achievable through traditional breeding methods should not be subject to the same stringent regulations as GMOs, streamlining the approval process for these innovations. Still, more complex modifications involving foreign DNA would still fall under existing GMO regulations, maintaining a layer of oversight on more radical genetic alterations. However, there is still no global framework, and as we've seen already, biology has a tendency to replicate and evolve in unpredictable ways. The developments in China and the EU reflect an urgent global need to update and reform regulatory frameworks for genome-edited crops, driven by a desire to foster innovation while ensuring safety and maintaining public confidence. As countries continue to adapt their policies, further changes will shape the future of agricultural biotechnology, potentially making genome-edited crops more accessible and widely used across the globe.

Regulating DNA Recognition Systems

Can you produce a photo of someone's face solely from their DNA? In the US, police detectives used a DNA sample to generate a 3D model of a suspect's face using facial recognition tools. Detectives from California's East Bay Regional Park District Police Department decided to use genetic information from a 1990 cold case involving the death of Maria Jane Weidhofer to create a lead. They sent the DNA from the crime scene to Parabon NanoLabs, which specializes in generating faces from DNA. Using machine learning, Parabon produced a 3D image of a potential suspect based on the DNA evidence—not a real photograph but a predicted appearance including skin tone, eye and hair color, and other facial features. The company even incorporated a haircut and mustache based on a witness' description, not the DNA. In a move to gather public tips, the police department released this generated face, leading (unsurprisingly) to controversy. In 2020, more controversy ensued when a detective requested to run the DNA-based facial reconstruction through facial recognition software, a move considered problematic by civil liberties experts and against Parabon NanoLabs' policies. But while this was one of the first known instances of a police department using this tactic, the question of how and when to use someone's DNA is increasingly common. The COVID-19 pandemic accelerated widespread use of infectious disease surveillance techniques, from saliva tests at airports and border crossings, to nasal swabbing at testing centers. To ease testing bottlenecks, which sometimes resulted in hours-long lines, alternative testing centers opened up: Private companies dispatched workers, who often had no medical training, to vans or small tents to administer PCR or rapid response tests. It wasn't immediately clear where the test results would be sent, or who might also gain access to the data. With the growing size and scale of third-party test results and genetic databases, anyone with the right skills could identify individuals—and we don't yet have safeguards against widespread genetic surveillance. As of the start of 2024, there are few restrictions on private companies buying and selling genetic data in the US and in many places around the world.

Safeguarding Genetic Privacy

Genetic privacy will be increasingly difficult to safeguard—yet big genetic data sets are required to perform the kind of research that leads to new therapeutics. Sharing a person's complete genetic code online can help scientists but also poses privacy risks, as people with bad intentions might use it to learn about the health of an individual or their family. Recently, experts have started using AI to generate artificial, but scientifically useful, genetic data that keeps people's identities safe.

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Scientists at the University of Tartu, Estonia, use neural networks to develop novel segments on human genomes. Because genetic data is sensitive, the hope is that an artificial human genome will allow researchers to study DNA without infringing on anyone's privacy. Researchers at the University of Montpellier in France developed a novel method that uses both AI and known information about how genes change in our bodies to work with big data sets more easily. They cut genetic data from thousands of people from different backgrounds into pieces, based on where genes often mix during reproduction, and used it to train the AI system. It now creates artificial populations of genetic data that are diverse and realistic but don't risk anyone's privacy.

Defining Parenthood

The relationship between creating a child and being the parent of that child is becoming more complex due to advances in reproductive technology and changes in the law. Emerging technologies like induced pluripotent stem cells (see: Growing Sex Cells trend) will someday allow children to be conceived with synthetic eggs and sperm or grown in artificial wombs, challenging society's current ideas about procreation and parenthood. In the UK, regulators are considering reforms to make surrogacy simpler and to address the issue of commercial surrogacy, which is technically illegal but practiced in a gray area. One controversial proposal is to allow surrogacy without a genetic link between the child and the commissioning parents, which raises questions about whether this constitutes assisted reproduction or a form of adoption. The reforms also consider granting commissioning parents full parental rights from birth, moving away from the surrogate's default parental rights. These discussions highlight the tension between the desire for genetic parenthood and reproductive freedom, especially in cases where a biological connection to the child does not exist. Such debates will become increasingly relevant with the introduction of technologies like ectogenesis, potentially redefining what it means to "make" a baby and become a parent.

National DNA Drives

Several countries are in the process of developing their own national DNA databases, notably for the purpose of medical research advancement. The United Arab Emirates is currently working to sequence its entire population; the goal is to aid scientific research, as well as to map and sequence the genes of UAE nationals, which will assist in preventing and treating chronic illnesses. Because existing databases are overwhelmingly made up of Caucasian Americans and Europeans, people of Arab descent have been excluded from the benefits of genetic research. While the UAE's program is voluntary, there is a different strategy being used in China. Over the last decade, China has launched a comprehensive national effort to collect, sequence, and store the genetic information of its citizens, integrating DNA databases into a broader surveillance system fueled by the government's ambitions in artificial intelligence. This initiative has particularly targeted the Uyghur population, under the guise of public health programs like "Physicals for All," leading to the collection of genetic data without clear consent and raising concerns over privacy and human rights violations. As China builds a vast and unparalleled genetic database, encompassing both minority groups and the majority Han Chinese population, it faces minimal domestic opposition to its genetic research and surveillance practices, contrasting with the ongoing debates over genetic privacy in the US, Canada, the EU, and the UK.

International Collaborations to Advance Bioengineering

Researchers are building the first-ever comprehensive map of all 37.2 trillion human cells in the body. The effort includes 130 software engineers, mathematicians, computational scientists, biologists, clinicians, and physicists hailing from Israel, the Netherlands, Japan, the UK, the US, and Sweden. Although a cell atlas has long been theorized, new biological tools and more powerful computers have turned this one-time vision into a reality. These scientists believe this mapping will give the medical community a new way of understanding how our bodies work and will help diagnose, monitor, and treat disease.

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Resolving Bias in Genome Research

Overwhelmingly, the majority of people who have had their genomes sequenced come from affluent Caucasian Americans and Europeans; fewer than 2% are from Africa. This excludes an enormous number of people from the benefits of genetic research, so there is now increased attention and funding to diversify this pool. H3Africa works with African investigators to determine genomic and environmental determinants of common diseases. The Non-Communicable Diseases Genetic Heritage Study consortium, based in Nigeria, is creating a comprehensive catalog of human genetic variation among Nigerians. A decade-long Three Million African Genomes project is also underway to locate missing genetic variants from ancestral genomes in Africa. It would build an African biobank of clinical information and could lead to a more equitable future of genetic research.

Ethics in Indigenous Genomics

Biological materials from Indigenous peoples are still missing from genetic databases, basic research, and clinical studies. One major reason why can be traced back to how members of the Havasupai tribe were treated by Arizona State University (ASU) in the late 20th century. In 1990, Havasupai were grappling with an increase in diabetes. They allowed ASU researchers to collect blood samples, hoping the research would help them eradicate the disease. But then, unbeknownst to the Havasupai, the researchers changed the scope of the project to encompass genetic markers for alcoholism and various mental disorders. They went on to publish many papers in academic journals highlighting their results, which led to news stories about inbreeding and schizophrenia among tribe members. The Havasupai were, understandably, horrified and humiliated, and they filed a lawsuit against ASU in 2004. ASU eventually settled the suit in 2010, returned the blood samples to the tribe, and promised not to publish any more research. Subsequently, the Navajo Nation, the second-largest group of Indigenous peoples in the US, banned all genetic sequencing, analysis, and related research on its members. Although their objections were absolutely warranted, they've led to another problem: The pool of genetic data in the US doesn't include Indigenous peoples. New initiatives could make genetic datasets and research more inclusive. The Summer Internship for Indigenous Peoples in Genomics trains budding scientists, while the Center for the Ethics of Indigenous Genomic Research works to promote Indigenous-led research in biobanking and precision medicine. Canada and New Zealand are both working on governing frameworks and libraries to include Indigenous peoples, relying on direction from local communities.

Posthumous Sperm Retrieval

In the wake of the Hamas terrorist attack on October 7, 2023, when hundreds of young men were among the Israelis who lost their lives, there was an unprecedented surge in requests for posthumous sperm retrieval (PSR) by embryologists and IVF specialists. This process involves retrieving viable sperm from the deceased's testicular tissue shortly after death and preserving it in liquid nitrogen. Families sought to preserve their loved one's genetic legacy by extracting and freezing their sperm, hoping for the possibility of conceiving a child in the future. As a previously rare procedure, PSR required a family court order in Israel for unmarried men, while the spouse of a married individual could directly request the procedure. But the crisis led to Israel's Ministry of Health easing regulations, allowing hospitals to process requests from parents without court involvement. It also brought PSR into mainstream view, raising questions about whether it is ethical to retrieve and use sperm after death.

Gene Editing Ethics

In 2018, Chinese scientist He Jiankui caused a global uproar by announcing he had created the world's first gene-edited children using CRISPR technology, targeting embryos to make them resistant to HIV. This led to the birth of twins, marking a controversial milestone in genetic editing. Jiankui's actions, deemed "illegal medical practices" in China, resulted in a three-year prison sentence for him and his two associates, partly because the genetic alterations could be passed down to future generations. Following the scandal, China

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tightened regulations on human gene editing and banned He from conducting any reproductive technology services. Despite these restrictions, late in 2023, He proposed a new study focused on editing mouse and human embryos to investigate potential protection against Alzheimer's disease, citing the urgent need to address the challenges posed by an aging population and the current lack of effective treatments for Alzheimer's. His latest proposal has reignited ethical debates and concerns within the scientific community. The proposal's reception remains mixed, reflecting ongoing dilemmas over the boundaries of genetic research.

A dozen countries have now banned germ line engineering in humans, though their ranks do not include China, which tightened regulations without banning the practice outright. Federal law in the US regulates the use of federal funds for research on human germline gene therapy—laws are notoriously politicized and have changed a few times in the past decade. The EU's Convention on Human Rights and Biomedicine said tampering with the gene pool would be a crime against human dignity and human rights. But all those declarations were made before it was actually possible to precisely engineer the germ line. Now, with CRISPR, it is possible.

Engineering Super Soldiers

Last year, a team of military medical scientists in China reported that they had enhanced human embryonic stem cells' resistance to radiation by inserting a gene from the water bear, a microorganism known for its extreme survivability. Using CRISPR technology, they achieved a high survival rate of these modified cells under lethal radiation exposure. The research, led by professor Yue Wen at the Academy of Military Sciences in Beijing, has sparked interest (read: alarm) since its publication, because of the implication: What if this is used to create a new version of superhumans, capable of surviving extreme conditions like nuclear fallout? Scientists around the world raised concerns about the safety and ethical implications of transferring genes across species, with the risk of harmful mutations or unknown immune responses. The team plans to further their research by transforming these modified cells into blood-making cells to help humans survive acute radiation sickness, suggesting additional benefits in protecting against diseases such as cancer and diabetes. The experiment was deemed legal as it was conducted on cultured cell lines in a lab. But what happens when that research is ready to leave the lab for the real world?

Some researchers are concerned that biological experimentation could someday produce supersoldiers who have been enhanced with special capabilities.

Image credit: Image credit: Future Today Institute and Dall-E.

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AMY WEBB

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Recognized as the global leader in strategic foresight, Amy Webb advises business leaders through disruptive change, enabling them to navigate an unpredictable future with confidence and take actions that address global challenges, create sustainable value, and ensure a company's long-term growth. As founder and CEO of the Future Today Institute, Amy pioneered a unique quantitative modeling approach and data-driven foresight methodology that identifies signals of change and emerging patterns very early. Using that information, Amy and her colleagues identify white spaces, opportunities, and threats early enough for action. They develop predictive scenarios, along with executable strategy, for their global client base. In 2023, Amy was recognized as the #4 most influential management thinker in the world by Thinkers50, a biannual ranking of global business thinkers. She was also featured on the 2021 Thinkers 50 list, was shortlisted for the 2021 Digital Thinking Award, and received the 2017 Thinkers50 Radar Award. Forbes called Amy "one of the five women changing the world," and she was honored as one of the BBC's 100 Women of 2020.

Amy also serves as a professor of strategic foresight at New York University's Stern School of Business, where she developed and teaches the MBA-level strategic foresight course with live case studies. She is a Visiting Fellow at Oxford University's Säid School of Business. She was elected a life member of the Council on Foreign Relations and is a member of the Bretton Woods Committee. She is a Steward and Steering Committee Member for the World Economic Forum, a founding member of the Forum's Strategic Foresight Council, a member of the Forum's Risk Advisory Council, and serves on the Forum's Global Futures Council. She was a Delegate on the former U.S.-Russia Bilateral Presidential Commission, representing US interests in technology.

Regarded as one of the most important voices on the futures of technology (with specializations in both AI and synthetic biology), Amy is the author of four books, including the international bestseller The Big Nine and her most recent, The Genesis Machine, which was listed as one of the best nonfiction books of 2022 by The New Yorker. To date, her books have been translated into 19 languages. A widely published and quoted thought leader, Amy regularly appears in a wide range of publications and broadcasts.

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METHODOLOGY

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In continuous publication since 2007, Future Today Institute's annual report includes maturing and emerging trends grouped into two categories: industry and technology. Industry trends reflect the ways in which technology is shaping the future of an entire industry. Technology trends are specific developments within one arena, such as artificial intelligence. Covering a wide range of technologies across industry sectors creates a holistic view of change and provides leaders with a clear understanding of their potential impact. Trends are published as individual Industry and Technology reports, as well as in one combined report with all of our research.

Monitored regularly, trends help executives recognize emerging threats and opportunities in the near-term and enable them to develop perspectives, strategies and plans for the future.

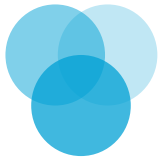
Future Today Institute's Strategic Foresight Methodology

SIGNALS & LONG-TERM TRENDS

What is INFLUENCING the future?

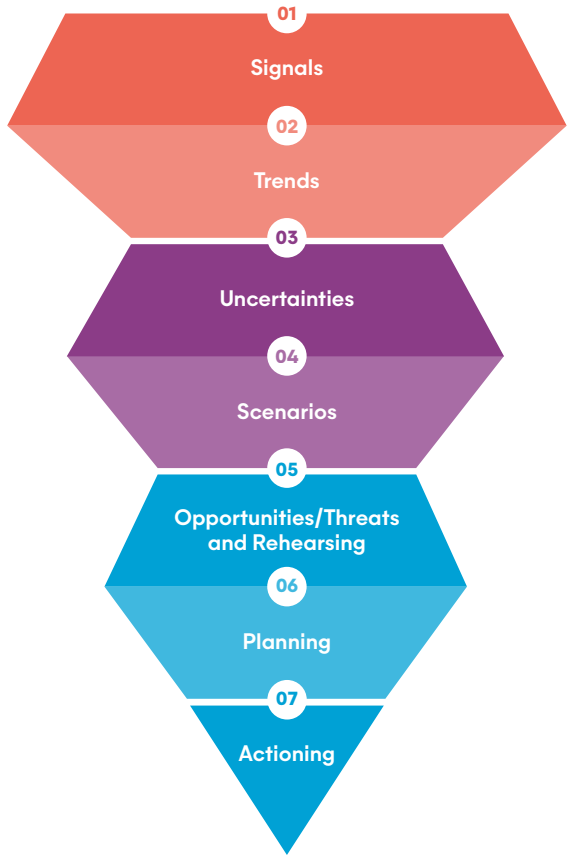
GLOBAL MACRO SCENARIOS

What is THE future?



STRATEGIC

What is YOUR ORG'S future?



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