McKinsey
Global Institute

Executive summary

The Bio Revolution

Innovations transforming economies, societies, and our lives

May 2020

McKinsey Global Institute

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MGI is led by three McKinsey & Company senior partners: co-chairs James Manyika and Sven Smit, and director Jonathan Woetzel. Michael Chui, Susan Lund, Anu Madgavkar, Jan Mischke, Sree Ramaswamy, Jaana Remes, Jeongmin Seong, and Tilman Tacke are MGI partners, and Mekala Krishnan is an MGI senior fellow.

Project teams are led by the MGI partners and a group of senior fellows and include consultants from McKinsey offices around the world. These teams draw on McKinsey's global network of partners and industry and management experts. The MGI Council is made up of McKinsey leaders and includes Michael Birshan, Andrés Cadena, Sandrine Devillard, André Dua, Kweilin Ellingrud, Tarek Elmasry, Katy George, Rajat Gupta, Eric Hazan, Acha Leke, Gary Pinkus, Oliver Tonby, and Eckart Windhagen. The Council members help shape the research agenda, lead high-impact research and share the findings with decision makers around the world. In addition, leading economists, including Nobel laureates, advise MGI research.

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Preface

Advances in biological sciences, combined with the accelerating development of computing, data processing, and artificial intelligence (AI), are fueling a new wave of innovation that could have significant impact in sectors across the economy, from healthcare and agriculture to consumer goods and energy.

This report describes the potential scope and scale of this wave of innovation and highlights the profound risks that will need to be managed. We conclude with a look at the potential implications for a range of stakeholders. The research began in early 2019, many months before the novel coronavirus SARS-CoV-2 causing the COVID-19 infection appeared and triggered a global pandemic in the first quarter of 2020. The early response to COVID-19 illustrated the substantial advances in biological science in just the past few years. The speed with which scientists sequenced the virus's genome—weeks rather than months—bore witness to the new world of biology we describe in this report. Sequencing is just the start: bio innovations are enabling the rapid introduction of clinical trials of vaccines, the search for effective therapies, and a deep investigation of both the origins and the transmission patterns of the virus. While this report does not explore the relevance of ongoing bio innovation to tackling COVID-19 in depth, we do believe that the pandemic makes this research even more acutely relevant.

The McKinsey Global Institute (MGI) has an active research program focused on research on technologies and their impact on business, the economy, and society, including in digital technology, AI, and biology. In May 2013, we published a report, *Disruptive technologies: Advances that will transform life, business, and the global economy*, that focused on biology as one of the arenas. Our 2017 report on automation, *A future that works: Automation, employment, and productivity,* highlighted the productivity potential of fast-evolving technologies but also looked at the technical and nontechnical factors that would determine the pace and extent of adoption. That same year, we published *Artificial intelligence: The next digital frontier?*, which examined how AI will unleash the next wave of digital disruption and what companies should do to prepare for it. McKinsey has also published reports on healthcare topics, including *The big-data revolution in US health care: Accelerating value and innovation* in 2013. In 2020, MGI plans to publish a major report on health and economic growth.

We owe a great deal to the wealth of academic and technical research into the many aspects of this wave of innovation. Building on MGI's expertise in analyzing the economic implications of major global trends, we surveyed the scientific advances and explored nearly 400 use cases, drawing out the implications for businesses, economies, and broader society. This research builds on previous MGI work on different types of disruptive technology, including big data, the Internet of Things, and, most recently, automation and AI. The project team worked closely with an MGI team researching global health issues in collaboration with McKinsey experts in public health and healthcare systems, and pharmaceuticals and medical products. We hope that this report contributes to a better understanding of the applications, potential, and risks of the advances in biological sciences and provokes further discussion among business leaders, policy makers, civil society, and the public on the potential benefits and trade-offs of these technologies given that they come with profound and unique risks.

The research was led by Michael Chui, MGI partner in San Francisco; Matthias Evers, a McKinsey senior partner based in Hamburg and McKinsey's global leader of R&D in pharmaceuticals and medical products; and James Manyika, McKinsey senior partner and co-chair of MGI. The work was also guided by Sven Smit, who also co-chairs MGI, and Jonathan Woetzel, MGI director in Shanghai. Alice Zheng and Travers Nisbet led the project team, which comprised Tom Colocci, Kevin Hwang, Maliha Khan, Archana Maganti, Morgan Paull, Anneke Maxi Pethö-Schramm, and Donna Xia. We thank Chloe Rivera and George Wang for leading the exploratory phase. We are grateful for the support of, and close collaboration with, Jaana Remes, Aditi Ramdorai, and Thilo Rattay on MGI research on global health issues. We also appreciated the opportunity to collaborate with Tim Dickson and Astrid Sandoval of *McKinsey Quarterly* and with Felix Rölkens, Shrina Poojara, and Marilena Schmich of McKinsey's *The state of fashion 2020* report.

We give special thanks to many external experts who informed aspects of our research with their expertise and insights, including Russ B. Altman, Kenneth Fong Professor of Bioengineering, Genetics, Medicine, Biomedical Data Science and (by courtesy) Computer Science at Stanford University; Eric Bartels, global head of biological research and development, Indigo; Sebastian A. Brunemeier, chief investment officer and co-founder, Cambrian Biopharma Ventures; Jonah Cool, science program officer, Chan Zuckerberg Initiative;

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While we are grateful for all the input we have received, the report and views expressed here are ours alone. We welcome your comments on this research at MGI@mckinsey.com.

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In brief

The Bio Revolution

A confluence of advances in biological sciences—decades in the making—with the accelerating development of computing, automation, and artificial intelligence (AI), is fueling a new wave of innovation that could have significant impact on economies and societies, from health and agriculture to consumer goods and energy. These new capabilities and applications are already improving our response to global challenges from climate change to pandemics; at the time of writing this report, they were being used to help respond to the COVID-19 pandemic. But these innovations come with profound risks, arguing for a serious and sustained debate about how this innovative wave should proceed. This report assesses progress in these innovations, their potential for economic and societal impact, and the risks involved. Key findings include the following:

— **Increasing ability to understand and engineer biology.** Recent advances include a sharp drop in the cost of sequencing DNA and the emergence of new techniques (including CRISPR) to edit genes and reprogram cells. So far, innovation in four arenas stands out: (1) biomolecules—the mapping, measuring, and engineering of molecules; (2) biosystems—the engineering of cells, tissues, and organs; (3) biomachines—the interface between biology and machines; and (4) biocomputing—the use of cells or molecules such as DNA for computation. All show various rates of progress from demonstration to commercial use.

— **Transformative new capabilities.** These innovations are creating five new potentially transformative capabilities: (1) biological means could be used to produce a large share of the global economy's physical materials, potentially with improved performance and sustainability; (2) increased control and precision in methodology is occurring across the value chain from delivery to development and consumption with more personalization; (3) the capability to engineer and reprogram human and nonhuman organisms is increasing, potentially improving disease prevention and treatment as well as agricultural performance; (4) new methodologies using automation, machine learning, and proliferating biological data are enhancing discovery, throughput, and productivity in R&D; and (5) potential is growing for interfaces between biological systems and computers to, for instance, restore sensory function to the brain, and for biocomputers that could use DNA to store data.

— **Substantial potential direct and indirect impact.** As much as 60 percent of the physical inputs to the global economy could, in principle, be produced biologically—about one-third of these inputs are biological materials (wood or animals bred for food) and the remaining two-thirds are nonbiological (plastics or fuels) but could potentially be produced or substituted using biology. Therefore, it is possible that bio innovations could impact up to 60 percent of physical inputs, although attaining that full potential is a long way off. Even modest progress toward it could transform economies, societies, and our lives, including what we eat and wear, the medicines we take, the fuels we use, and how we construct our physical world. In human health, at least 45 percent of the current global disease burden could be addressed using science that is conceivable today.

- **Visible pipeline of applications.** Around 400 use cases, almost all scientifically feasible today, can be observed, mainly in human health and performance; agriculture, aquaculture, and food; consumer products and services; and materials, chemicals, and energy production. These use cases alone—more than half of which fall outside human health—could have direct economic impact of up to $4 trillion a year over the next ten to 20 years. The full potential could be far larger if we take into account potential knock-on effects, new applications yet to emerge, and additional scientific breakthroughs.

- **Unique risks that require debate and mitigation.** New biological capabilities come with profound and unique risks that need serious, ongoing debate, and proactive, rather than reactive, approaches toward mitigation. One such risk is that biological systems are self-sustaining, self-replicating, and interconnected, with potentially cascading and long-lasting effects on entire ecosystems or species; once Pandora's box is opened, we could have little control over what happens next. Access to these tools may be relatively cheap and easy, making the potential for misuse considerable. Privacy and consent issues abound due to new forms of biological data. Responding to such challenges through cooperation and coordination may be complicated given competitive and commercial incentives and varying jurisdictional or cultural value systems.

- **The timing of applications' adoption and impact hinges on multiple factors.** Adoption timelines, and therefore impact, will vary depending on several factors, including society's approach to risks. There are three stages in the journey from lab to market: scientific research, commercial availability, and diffusion at scale. Science needs investment and to be proven. Resulting applications need to offer a value proposition against existing offerings, and able to be scaled. Diffusion and eventual impact will depend on public sentiment and mechanisms governing the use of different applications. About 70 percent of the total potential impact could hinge on societal attitudes and the respective mechanisms employed to govern use, such as regulations and societal norms.

- **Stakeholders and contributors need to inform themselves about the Bio Revolution.** Innovators, businesses, governments, and citizens need to become bio-literate in order to respond effectively to ongoing bio innovation, weighing risk against reward. The choices they make will influence the size and scope of the Bio Revolution's benefits for economies, societies, and the planet.

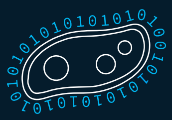
The Bio Revolution

Four arenas of bio innovations

Biomolecules
Mapping and engineering intracellular molecules

Biosystems
Mapping and engineering cells, tissues, and organs

Biomachine interfaces
Connecting nervous systems of living organisms to machines



Biocomputing
Using cells and cellular components for computation

The scope and scale of the potential impact on economies and societies appear substantial

60% of the world's physical inputs could be made using biological means

45% of the world's disease burden could be addressed

30% of private-sector R&D spent in biology-related industries

Transformative new capabilities…

- Bio-based materials production
- Personalized and precision products and services
- Engineered organisms
- Higher bio-based R&D productivity
- Bio-machine interfaces and computing

…with applications across domains

Examples of applications

Agriculture
Meats produced without animals

Energy and materials
Synthetic silks produced by microbe factories

Health
Monogenic diseases prevented at birth

Consumers
Personalized diets based on your genome

…but risks and issues to manage

- Self-replicating, bio crossing borders
- Unintended consequences
- Low barriers to potential misuse
- Hard to forge consensus
- Privacy and consent concerns
- Inequitable access or effects

$2T–$4T

of annual direct economic potential globally in 2030–40
(significantly higher with downstream and secondary effects)

Innovators, businesses, and policy makers must act if we are to capture the benefits of the Bio Revolution, while engaging together in a sustained dialogue about how to use these innovations

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Executive summary

Nearly seven decades after the double helix structure of a DNA molecule was discovered, the world of biology appears to have reached a new phase of growth. A flurry of recent innovations—such as CRISPR–Cas9 to edit genes and stem cell advances to reprogram cells—are providing new understanding, new materials, and new tools, as well as lower costs. The science is so advanced, for example, that in 2016, a Human Cell Atlas project was kicked off to create comprehensive reference maps of all human cells as a basis for research, diagnosis, monitoring, and treatment. Moreover, as a result of the scientific advances, a growing number of applications are emerging from the lab and being put to commercial use.[1]

The potential for beneficial economic and social impact seems enormous. As much as 60 percent of the physical inputs to the global economy could, in principle, be produced biologically. Our analysis suggests that around one-third of these inputs are biological materials, such as wood, cotton, and animals bred for food. For these materials, innovations can improve upon existing production processes. For instance, squalene, a moisturizer used in skin-care products, is traditionally derived from shark liver oil and can now be produced more sustainably through fermentation of genetically engineered yeast. The remaining two-thirds are not biological materials—examples include plastics and aviation fuels—but could, in principle, be produced using innovative biological processes or be replaced with substitutes using bio innovations. For example, nylon is already being made using genetically engineered microorganisms instead of petrochemicals. To be clear, reaching the full potential to produce these inputs biologically is a long way off, but even modest progress toward it could transform supply and demand and economics of, and participants in, the provision of physical inputs. Biology has the potential in the future to determine what we eat, what we wear, the products we put on our skin, and the way we build our physical world.

Human health is one of the most significant domains where biological advances are being applied. Biology is already helping save lives through innovative treatments tailored to our genomes and microbiomes. In the future, we estimate that almost half of the global disease burden could be addressed through applications that are scientifically conceivable today. Moreover, many of the innovations born of these bio innovations contributed to the global response to the SARS-CoV-2 pandemic in early 2020 (see Box E1, “An April 2020 snapshot of early contributions by bio innovations in the fight against COVID-19,” at the end of this executive summary).

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[1] DNA is short for deoxyribonucleic acid, an organic chemical found in all cells and in many viruses. DNA acts as the main carrier for genetic information. CRISPR-Cas9 stands for clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9. This tool uses a small piece of ribonucleic acid (RNA) with a short “guide” sequence that attaches to a target sequence of DNA and to the Cas9 enzyme. The Cas9 enzyme cuts the targeted DNA at the targeted location, which enables genetic material to be added or deleted. In the rest of this report, we refer to the tool as CRISPR. RNA is a biopolymer consisting of ribose nucleotides (nitrogenous bases appended to a ribose sugar molecule) connected and forming strands of varying lengths. Unlike most DNA molecules composed of two biopolymer strands, RNA typically is a single-stranded biopolymer. RNA molecules play essential biological roles, from translating genetic information encoded in DNA molecules into the cellular structures and molecular machines (that is, proteins) to regulating the activities of genes. A stem cell is a type of cell in a multicellular organism that has two capabilities: self-renewal by producing indefinitely more cells of the same type, and the ability to give rise to many other kinds of cells in the body by differentiation.

Many other domains, from agriculture to energy, could also benefit from biological processes and products. Biology could even be deployed to mitigate climate change, by helping reduce net man-made greenhouse gas (GHG) emissions.

However, the risks from these innovations are profound and unique. Biological systems self-replicate, are self-sustaining, and are highly interconnected; changes to one part of a system can have cascading effects and unintended consequences across an entire ecosystem or species. Accidents can have major consequences—and, especially if used unethically or maliciously, manipulating biology could become a Pandora's box that, once opened, unleashes lasting damage to the health of humans, ecosystems, or both. The risks are particularly acute because many of the materials and tools are relatively cheap and accessible. Moreover, tackling these risks is complicated by a multiplicity of jurisdictional and cultural value systems, which makes collaboration and coordination across countries difficult.

This report, which draws on a wealth of academic and technical research, takes a detailed look at how advances in biological science and their practical application could transform our economy and society. We have compiled a library of about 400 visible use cases that, while not comprehensive, nonetheless point to the domains that could be most directly affected—and hint at the potential economic value that could be created. We also focus on the considerable challenges that will need to be overcome to turn biology's economic potential into reality in scientific research, commercialization, and diffusion. By our estimate, more than two-thirds of the total impact could hinge on consumer, societal, and regulatory acceptance of these applications. A new era is dawning that we refer to as the Bio Revolution. Like all periods of economic and technological disruption, it is an era of both great opportunity and considerable uncertainty.

Bio innovation is occurring in four key arenas

A wave of innovation is being enabled by advances in biological sciences accelerated by developments in computing, data analytics, machine learning, AI, and biological engineering. We group innovations into four arenas: biomolecules, biosystems, biomachine interfaces, and biocomputing (Exhibit E1).[2]

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[2] Our definition of biomolecules for this report covers the mapping and measuring of intra-cellular components (for example, DNA, RNA, and proteins) in the study of omics. We also include the engineering of intra-cellular components (for instance, genome editing). Our definition of biosystems covers engineering at the cell, tissue, or organ level, including stem-cell technologies and transplantation use cases. Biomachine interfaces is a field of biology defined as the connection of nervous systems of living organisms to machines, including in brain-machine interfaces. Biocomputing is a field of biology defined as using cells and cellular components for computational processes (storing, retrieving, or processing data).

Exhibit E1

Bio innovation is occurring in four key arenas.

	Biomolecules	**Biosystems**	**Biomachine interfaces**	**Biocomputing**
Definitions				
Mapping	Cellular processes and functions via measuring intracellular molecules (eg, DNA, RNA, proteins) in the study of omics	Complex biological organizations and processes, and interactions between cells	The structure and function of nervous systems of living organisms	Intracellular pathways or networks of cells to return outputs based on specific conditions (for computation)
Engineering[1]	Intracellular molecules (eg, via genome editing)	Cells, tissues, and organs, including stem cell technologies and transplantation	Hybrid systems that connect nervous systems of living organisms to machines	Cells and cellular components for computational processes (storing, retrieving, processing data)
Examples	Gene therapy for monogenic diseases	Cultured meat grown in a lab	Neuroprosthetics for motor control (implant or external headset) of human or robotic limb	Data storage in strands of DNA

1. Design, de novo synthesis, or modification.
Source: McKinsey Global Institute analysis

Major breakthroughs in each of the four arenas are reinforcing one another. In biomolecules and biosystems, advances in omics and molecular technologies—the mapping and measuring of molecules and pathways within cells, and engineering them—are enhancing our understanding of biological processes, as well as enabling us to engineer biology (Exhibit E2).[3] For example, CRISPR technology allows scientists to edit genes more quickly and precisely than previous techniques. Advances in biomachines and biocomputing both involve deep interaction between biology and machines; it is becoming increasingly possible to measure neural signals and power precise neuroprosthetics.[4] It is now also possible to store the world's wealth of data using DNA—by some measures one kilogram of DNA could hypothetically store all current data in the world.[5]

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[3] Omics is a collective term for technologies that allow the comprehensive identification and quantification of the complete set of molecules (for instance, proteins, carbohydrates, and lipids) of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time. Omics and molecular technologies is defined to cover the study of omics as well as technologies to engineer (design, synthesize, or modify) the same "omes."

[4] Neuroprosthetics are hybrid bionic systems that link the human nervous system to computers, thereby providing motor control and restoring lost sensory function of artificial limbs.

[5] Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016; and George I. Seffers, "Scientists race toward DNA-based data storage," *Signal*, September 1, 2019.

Worldwide DNA sequencing now creates huge volumes of biological data every year.[6] These technical advances, such as lower-cost sequencing or high-throughput screening, have helped lower the costs of entry, accelerate the pace of experimentation, and generate new forms of data to help us better understand biology. Advances at the single-cell level, such as single-cell imaging tools and single-cell ribonucleic acid (RNA) sequencing, are allowing scientists to build increasingly high-resolution maps of cells, which can be a basis for research, diagnosis, and treatment. Increasingly, the ability to understand and engineer biological processes exists across a variety of dimensions.

Exhibit E2

A range of scientific research streams are collectively known as omics.

Intracellular—flow of genetic information	**Epigenomics**	DNA modifications	Epigenetic marks that regulate gene expression (eg, DNA methylation, histone protein modification)	Regulation
	Genomics	DNA	Full genetic complement of an organism (DNA); relatively static over time	Transcription
	Transcriptomics	RNA	Complete set and quantity of RNA transcripts that are produced at a given time	Translation
	Proteomics	Protein	Entire set of proteins of an organism with changes over time	
Intracellular—products of metabolism	**Metabolomics**	Metabolite	Set of metabolites, small-molecule intermediates, and products of metabolism	
	Glycomics	Glycan	Structure and function of the complete set of glycosylated products (eg, glycans)	
	Lipidomics	Lipid	Complete set of lipids produced	
Other	**Microbiomics**	Microbe population	All microbes in a population (eg, the human gut)	
	Single-cell omics	Human and other cells	Captures single-cell-level nuances that aggregation across multiple cells would miss	
	Circulating cell-free DNA or RNA analysis	DNA/RNA in bloodstream, not in cell	Noninvasive genome or transcriptome information	

Source: McKinsey Global Institute analysis

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[6] Erika Check Hayden, "Genome researchers raise alarm over big data," *Nature*, July 1, 2015.

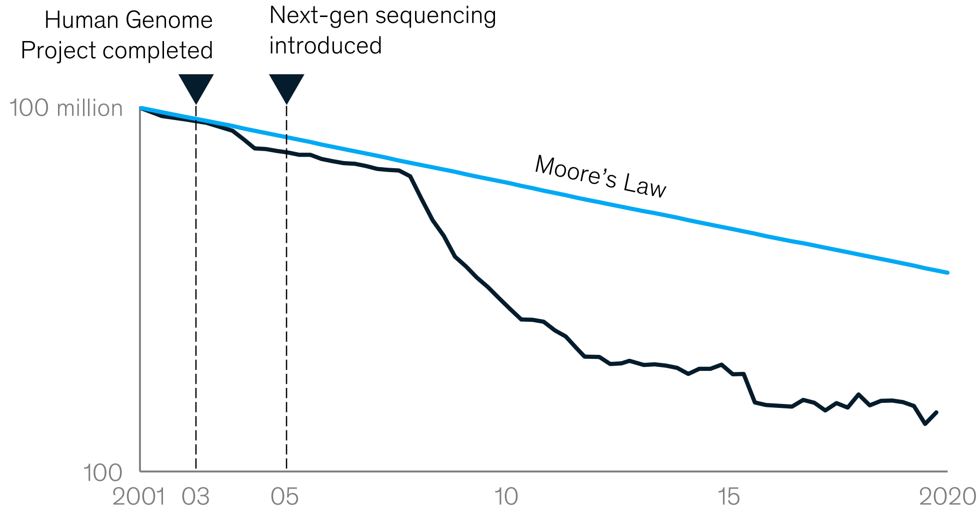
Mapping the genome is a foundational building block. This dates to the Human Genome Project, a 13-year, $3 billion journey to map the entire genetic makeup of humans, that began in 1990.[7] Accordingly, genomics is the most technologically advanced branch of omics, and has the most related applications either in development or already in use.[8] But other omics are necessary complements, and work on them is increasing. However, the power of the map of the human genome began to materialize only when sequencing DNA became cheaper and faster. The cost of DNA sequencing is now decreasing at a rate faster than Moore's Law (Exhibit E3).[9] In 2003, mapping the human genome cost about $3 billion; by 2019, it was less than $1,000. Within a decade or even sooner, the cost could be less than $100.[10]

Exhibit E3

Rapid advances in computing, bioinformatics, and AI are enabling the analysis of omics data.

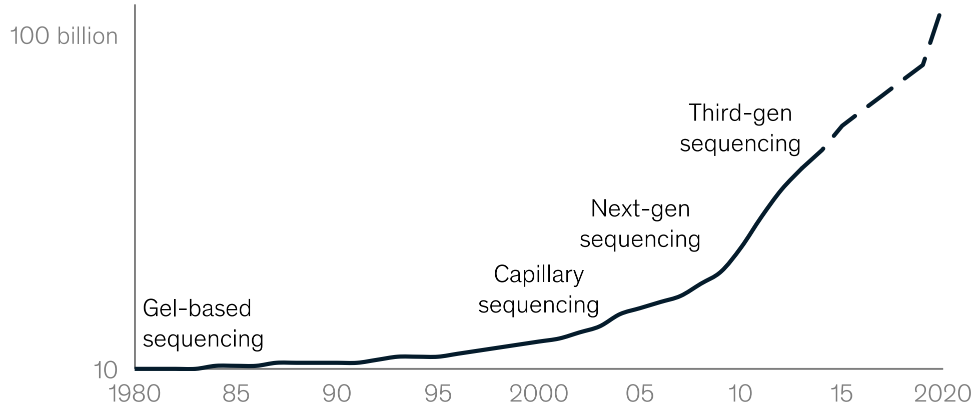
Cost per human genome[1]

$ (log scale)



Speed of sequencing

Kilobytes per day (log scale)



1. Data do not capture all costs associated with genome sequencing and include only production-related costs (labor, instruments, informatics, data submission).

Source: National Human Genome Research Institute; www.yourgenome.org; McKinsey Global Institute analysis

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[7] Human Genome Project Information Archive 1990–2003, https://web.ornl.gov/sci/techresources/Human_Genome/index.shtml.

[8] Genomics is the study of genes and their functions, and techniques related to them. The genome consists of the full genetic complement of an organism—its DNA.

[9] Moore's Law refers to the perception that the number of transistors on a microchip doubles every two years even while the cost of computers halves. See Gordon Moore, "Cramming more components onto integrated circuits," originally in *Electronics*, April 19, 1965, Volume 38, Number 8.

[10] Kristen V. Brown, "A $100 genome is within reach, Illumina CEO asks if world is ready," Bloomberg, February 27, 2019; Antonio Regalado, "China's BGI says it can sequence a genome for just $100," *MIT Technology Review*, February 26, 2020.

New biological capabilities could bring about transformational change in economies, societies, and our lives

New biological capabilities have the potential to bring sweeping change to economies and societies. The effects will be felt across value chains, from how R&D is conducted to the physical inputs in manufacturing to the way medicines and consumer products are delivered and consumed. These capabilities include the following:

- **Biological means could be used to produce a large share of the global economy's physical materials, potentially with improved performance and sustainability.** Significant potential exists to improve the characteristics of materials, reduce the emissions profile of manufacturing and processing, and shorten value chains. Fermentation, for centuries used to make bread and brew beer, is now being used to create fabrics such as artificial spider silk. Biology is increasingly being used to create novel materials that can raise quality, introduce entirely new capabilities, be biodegradable, and be produced in a way that generates significantly less carbon emissions. Mushroom roots rather than animal hide can be used to make leather.[11] Plastics can be made with yeast instead of petrochemicals.

- **Increased control and precision in methodology is occurring across the value chain, from delivery to development and consumption with more personalization.** Advances in biological sciences have made R&D and delivery processes more precise and predictable; the character of R&D is shifting from discovery by accident to rational design. Increasing knowledge of human genomes and the links between certain genes and diseases is enabling the spread of personalized or precision medicine, which can be more effective than the one-size-fits-all therapies of the past.[12] Precision also applies to agriculture, where insights from a plant or soil's microbiome increasingly can be used to optimize yield as well as to offer consumers with, for instance, personalized nutrition plans based on genetic tests.[13]

- **The capability to engineer and reprogram human and nonhuman organisms is increasing.** Gene therapies could offer complete cures of some diseases for the first time. The same technical advances that are driving capabilities that improve human health can be used to introduce valuable new traits that, for instance, improve the output or yield of nonhuman organisms like microbes, plants, and animals. Crops can be genetically engineered to produce higher yields and be more heat- or drought-resistant, for instance. By permanently genetically altering the vectors spreading disease (such as mosquitoes), gene drives could be used to prevent vector-borne diseases, including malaria, dengue fever, schistosomiasis, and Lyme disease, although they also come with ecological risks.[14]

- **New methodologies using automation, machine learning, and proliferating biological data are enhancing discovery, throughput, and productivity in R&D.** Biology and computing together are accelerating R&D, thereby addressing a productivity challenge. McKinsey analysis in 2017 found that the ratio of revenue to R&D spending in the biopharmaceutical industry hit a low point in productivity between 2008 and 2011.[15] An explosion of biological data due to cheaper sequencing can be used by biotech companies and research institutes that increasingly are using robotic automation and

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[11] Thomas Crow, "Mushroom leather: The key to sustainable fashion?," *Particle*, April 2019; and Eillie Anzilotti, "This very realistic fake leather is made from mushrooms, not cows," Fast Company, April 2018.

[12] For a fuller description, see, for example, *The Precision Medicine Initiative*, obamawhitehouse.archives.gov/precision-medicine.

[13] Chrysi Sergaki et al., "Challenges and approaches in microbiome research: From fundamental to applied," *Frontiers in Plant Science*, August 2018, Volume 9; Aleksandra A. Kolodziejczyk, Danping Zheng, and Eran Elinav, "Diet-microbiota interactions and personalized nutrition," *Nature Reviews Microbiology*, December 2019, Volume 17, Issue 12; Monica Reinagel, "Personalized nutrition: The latest on DNA-based diets," *Scientific American*, September 27, 2019; and Anna Vesnina et al., "Genes and eating preferences, their roles in personalized nutrition," *Genes*, April 2020, Volume 11, Issue 4.

[14] A gene drive is a technology that uses genetic engineering to enable a specific genetic variant to be passed from parent to child at a higher-than-normal rate (up to 100 percent).

[15] Sastry Chilukuri, Edd Fleming, and Ann Westra, *Digital in R&D: The $100 billion opportunity*, McKinsey & Company, December 2017.

sensors in labs that could increase throughput up to ten times.[16] Further, advanced analytics, more powerful computational techniques, and AI can be leveraged to provide better insights during the R&D process.

- **Potential is growing for interfaces between biological systems and computers.** A new generation of biomachine interfaces relies on close interaction between humans and computers. Such interfaces include neuroprosthetics that restore lost sensory functions (bionic vision) or enable signals from the brain to control physical movement of prosthetic or paralyzed limbs. Biocomputers that employ biology to mimic silicon, including the use of DNA to store data, are being researched. DNA is about one million times denser than hard-disk storage; technically, one kilogram of DNA could store the entirety of the world's data (as of 2016).[17]

While these are early days, the scope and scale of these emerging capabilities could have a broad impact on economies and societies, touching multiple domains both directly and indirectly. These applications may change everything from the food we consume to textiles to the types of health treatments we receive and how we build our physical world. The potential value is vast. As noted, as much as 60 percent of the physical inputs to the global economy could be produced biologically, and even modest progress toward that 60 percent number could be transformative.

Beyond the physical world, innovations could transform prevention, diagnostics, and treatment of disease. At least 45 percent of the global disease burden could be addressed with capabilities that are scientifically conceivable today, according to our analysis.

Bio innovations, such as high-throughput screening, CRISPR, and machine learning for analyzing large and complex biological data, have also begun to shape R&D. We estimate that roughly 30 percent of private-sector R&D in major economies is in industries where biological data, biological inputs, or biological means of production could be used.[18]

The full impact remains some way off in the future. But already, it is possible to identify some key applications and domains where these technologies could be deployed. Over the past five to ten years, proof-of-concept experimentation has increasingly emerged from the lab and moved into the marketplace. Many applications, particularly in health and agriculture, are now in the commercialization phase. Products from materials to chemicals are being substituted by alternatives produced and processed using biological means that are often more efficient and, in many cases, put less pressure on the environment. While the early direct impacts of biological technologies are for now primarily concentrated in certain domains, such as human health and agriculture, they could spread downstream to other sectors and society more broadly.

A visible pipeline of applications can deliver profound impact across a wide range of domains in the next two decades

To examine a wide range of applications, we compiled a library of about 400 use cases. They constitute an already-visible pipeline for the years ahead. Our library included use cases that are scientifically conceivable today and that could plausibly be commercialized by 2050. We excluded use cases that are not scientifically conceivable today or that are unlikely to have material commercial impact by 2050. The library is extensive, but not exhaustive—for instance, our research utilized publicly available data, but there are many applications being developed in private labs or in the defense industry where confidentiality reigns. We estimated the direct impact by sizing four value gain drivers: reduced disease burden;

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[16] *Zymergen case studies*, Partnership on AI, partnershiponai.org/case-study/zymergen/; Melanie de Almeida, *Taking biotech to the next level with laboratory automation*, Labiotech, November 14, 2018.

[17] Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016.

[18] R&D funded by business enterprise sector across major regions such as China, the EU, and the United States. Analysis is based on data from EU Industrial R&D Investment Scoreboard (2019).

improved quality; cost productivity; and environmental benefit. These estimates of potential value did not include knock-on effects. Using expert input and historical analogs, we then extrapolated our assessed impact to different time horizons by estimating the level and pace of adoption, as discussed below.[19]

Over the next ten to 20 years, we estimate that these applications alone could have direct economic impact of between $2 trillion and $4 trillion globally per year (Exhibit E4). Whether the impact is toward the bottom or top of that range will depend on how and when innovations are adopted. As we discuss below, significant uncertainty surrounds both scientific feasibility and commercial availability. The potential could be significantly higher if downstream and secondary effects are taken into account, as discussed in the next section.

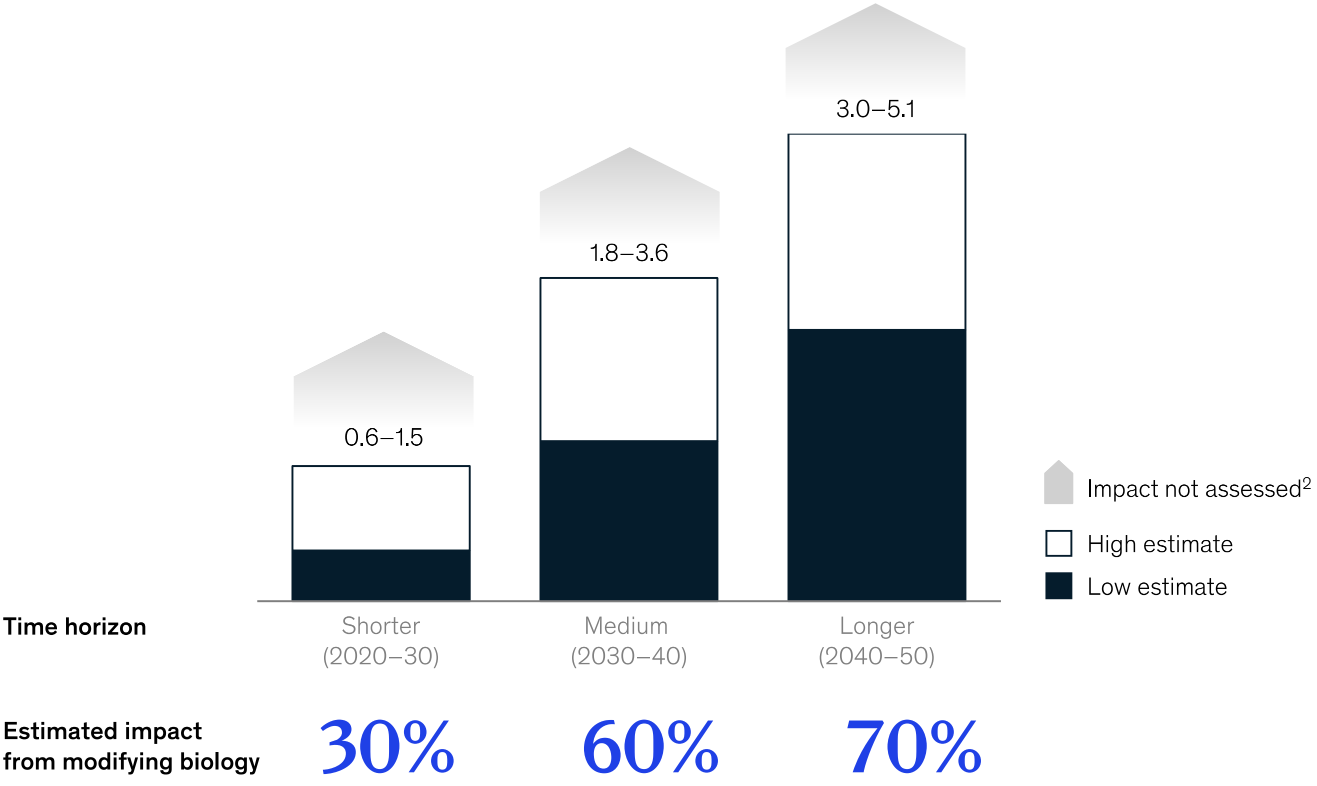
Human health and performance have the most scientific advances and the clearest pipeline from research to application. The science is advanced, and the market is generally accepting of innovations. However, based on our use cases, the impact could be more broad-based; in the next ten to 20 years, more than half of the direct impact is likely to be outside health, primarily in agriculture and consumer products (Exhibit E5).

Exhibit E4

In ten to 20 years, a visible pipeline of biological applications could create approximately $2 trillion to $4 trillion of direct annual economic impact.

Partial estimate of potential and direct annual impact by time horizon[1]

$ trillion



1. Current figures are based on potential direct annual economic impacts from 400 use cases examined, excluding non-omic economic impact from biocomputing and half of the biomachine applications.
2. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.

Source: McKinsey Global Institute analysis

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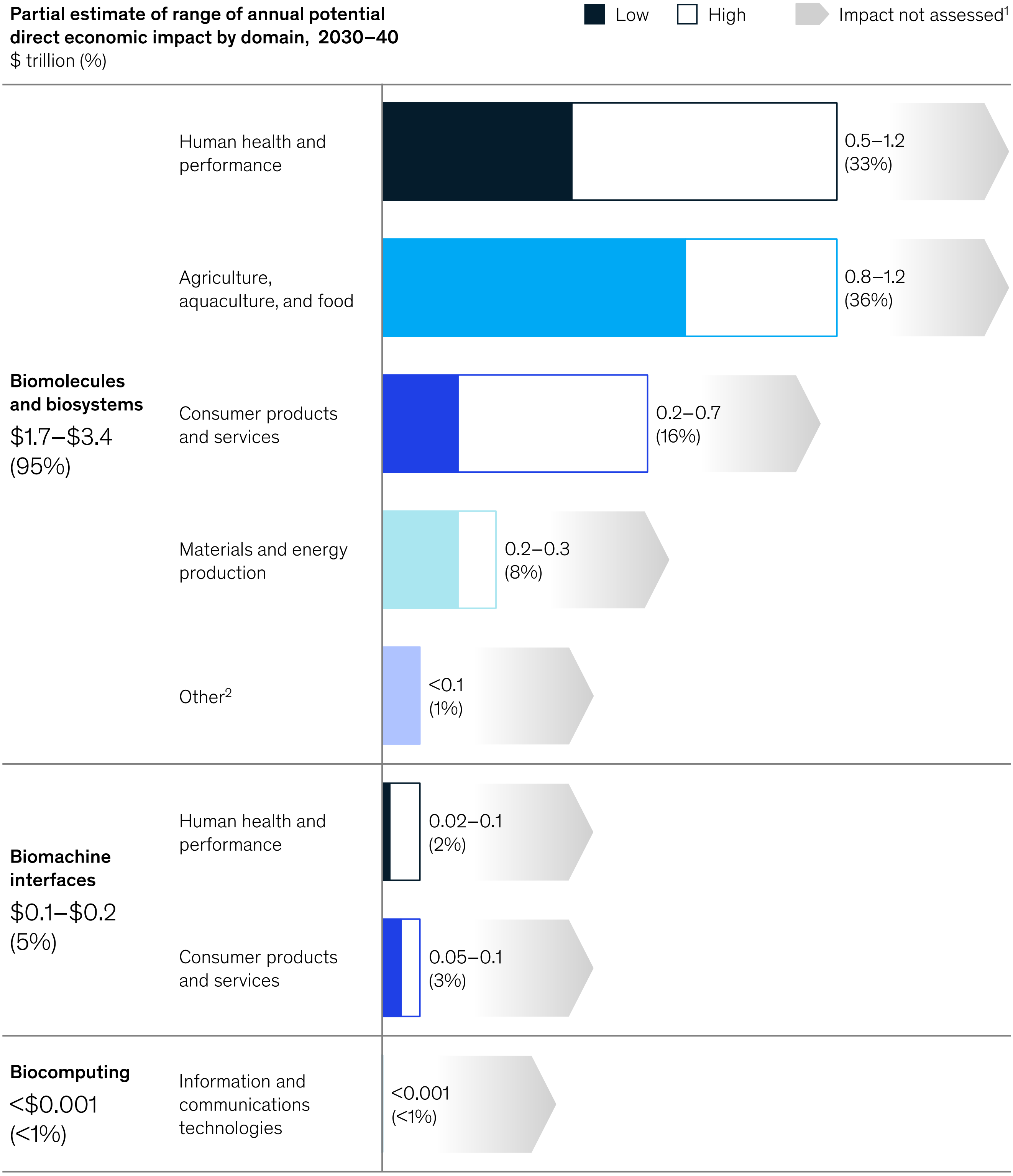
[19] For more on the methodology, please see chapter 4 and the technical appendix.

Exhibit E5

More than half of the impact from the visible pipeline of applications is outside of healthcare—in agriculture, consumer, and other areas.



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
2. Other applications include defense and security, undoing environmental harm, and education and talent.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation. Percentage of total impact is based on the midpoint of our estimated range of annual potential direct economic impact.

Source: McKinsey Global Institute analysis

Our library of use cases suggests that most value in the next one to two decades will come in four domains, or clusters of sectors where applications are emerging from bio innovation. Here we summarize use cases in each of these key domains (for a detailed snapshot, see illustration, "Applying the Bio Revolution for broad impact").[20]

- **Human health and performance.** A new wave of innovation is under way that includes cell, gene, RNA, and microbiome therapies to treat or prevent disease, innovations in reproductive medicine such as carrier screening, and improvements to drug development and delivery.[21] Many more options are being explored and becoming available to treat monogenic (caused by mutations in a single gene) diseases such as sickle cell anemia, polygenic diseases (caused by multiple genes) such as cardiovascular disease, and infectious diseases such as malaria.[22] We estimate between 1 and 3 percent of the total global burden of disease could be reduced in the next ten to 20 years from these applications—roughly the equivalent of eliminating the global disease burden of lung cancer, breast cancer, and prostate cancer combined. Over time, if the full potential is captured, 45 percent of the global disease burden could be addressed using science that is conceivable today. The direct annual global potential impact in this domain is estimated at $500 billion to $1.3 trillion over the next ten to 20 years, or 35 percent of the overall impact that we estimate for this period. The main capabilities enabling impact are the increased precision and personalization in the delivery of treatment and the accelerated pace and scope of R&D. In the longer term, innovations are likely to spread to more therapeutic areas such as cardiovascular and neurodegenerative diseases.

- **Agriculture, aquaculture, and food.** Applications such as low-cost, high-throughput microarrays have vastly increased the amount of plant and animal sequencing data, enabling lower-cost artificial selection of desirable traits based on genetic markers in both plants and animals.[23] This is known as marker-assisted breeding and is many times quicker than traditional selective breeding methods.[24] In addition, in the 1990s, genetic engineering emerged commercially to improve the traits of plants (such as yields and input productivity) beyond traditional breeding.[25] Historically, the first wave of genetically engineered crops has been referred to as genetically modified organisms (GMOs); these are organisms with foreign (transgenic) genetic material introduced.[26] Now, recent advances in genetic engineering (such as the emergence of CRISPR) have enabled highly specific cisgenic changes (using genes from sexually compatible plants) and intragenic changes (altering gene combinations and regulatory sequencings belonging to the recipient plant).[27] Other innovations in this domain include using the microbiome of plants, soil, animals, and water to improve the quality and productivity of agricultural production; and the development of alternative proteins, including lab-grown meat, which could take pressure off the environment from traditional livestock and seafood. Direct annual impact from all applications in this domain could be between about $800 billion and $1.2 trillion over the next ten to 20 years, or 36 percent of the total.

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[20] For an in-depth discussion of applications across domains studied in this research, see chapter 6.

[21] Carrier screening is a genetic test used to determine if a healthy person is a carrier of a recessive genetic disease. It provides life-lasting information about an individual's reproductive risk and their chances of having a child with a genetic disease.

[22] Polygenic diseases are caused by more than one gene. Examples of polygenic conditions include hypertension, diabetes, and coronary heart disease. There are often many environmental factors, too, making it more difficult to discern to what degree a disease is genetic even when the multiple genes are identified.

[23] A microarray is a high-throughput screening method where the DNA sequences representing the large number of genes of an organism, arranged in a grid pattern for detection in genetic testing.

[24] Marker-assisted breeding uses DNA markers associated with desirable traits to enable breeders to select a trait of interest without using transgenic approaches. Therefore, marker-assisted breeding doesn't produce genetically engineered organisms.

[25] National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*, Washington, DC: The National Academies Press, 2016.

[26] A GMO is an organism whose genetic material has been altered or modified. In GM crops, DNA from foreign organisms such as bacteria are introduced. See Kaare M. Nielsen, "Transgenic organisms—time for conceptual diversification?," *Nature Biotechnology*, March 2003, Volume 21, Issue 3.

[27] National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*, Washington, DC: The National Academies Press, 2016.

- **Consumer products and services.** Opportunities are opening up to use increasing volumes of biological data to offer consumers personalized products and services based on their biological makeup. Applications include direct-to-consumer (DTC) genetic testing, beauty and personal care based on microbiomes, and innovative approaches to wellness and fitness in both humans and pets. Some of these applications could have indirect impact on human health, such as wellness or fitness applications.[28] Annual direct economic impact over the next ten to 20 years in this domain could be $200 billion to $800 billion, or 19 percent of the total. Roughly two-thirds of this may come from the capability to personalize.

- **Materials, chemicals, and energy.** New biological ways of making and processing materials, chemicals, and energy could transform many industries and our daily lives, although the economics are challenging. Improved fermentation processes can increase the speed of production or quality of materials that are already created using fermentation (such as food and feed ingredients). Further, the creation of new bioroutes can enable the manufacture of more materials and chemicals biologically and the production of completely novel materials. Finally, advances are being made in energy, with greater use of biofuels, improving energy extraction, and improving energy storage. Applications include innovations related to production of materials such as improved fermentation processes, new bioroutes utilizing the ability to edit the DNA of microbes to develop novel materials with entirely new properties (self-repairing fabrics are one example), and building on advances in biofuels to innovate new forms of energy storage. Over the next ten to 20 years, the direct annual global impact could be $200 billion to $300 billion a year, or 8 percent of the total. This is a conservative estimate given uncertainty about what novel materials may emerge and the historical challenges of scaling innovations in this domain. About three-quarters of this economic potential is related to improved resource efficiency from new methods of production.

Biology has many other potential applications, although some of these are likely to be further in the future. It could be deployed to help the environment through biosequestration—using biological processes to capture carbon emissions from the atmosphere—and bioremediation, which is a process to remove inorganic and organic compounds from soil, water, and the atmosphere that might be harmful. Other potential applications could be found in education, defense, and even space exploration. While we expect biomolecules and biosystems innovations will drive the largest direct impact across the range of domains, impact is also emerging in biomachine interfaces and biocomputing, where the science and development are at an early stage but applications are promising. Applications that have already been developed include neuroprosthetics to restore hearing and vision.

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[28] We include wellness, nutrition, and fitness in consumer products and services rather than health because they tend to be consumed directly by individuals rather than mediated by healthcare professionals, offer more consumer choice compared to traditional health applications, and in some cases, such as fitness, require a significant change in consumer behavior to realize positive impact. This domain also includes beauty/enhancement use cases.

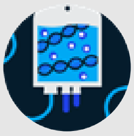
Applying the Bio Revolution …

Domain and examples | **Arenas of innovation** | **Transformational capabilities**

Human health and performance


Health optimization in future generations


Gene drives to reduce vector-borne diseases

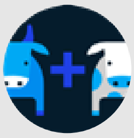

Cell-, gene-, and RNA-based approaches to prevent, diagnose, and treat diseases

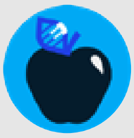

Improvements in drug development and delivery

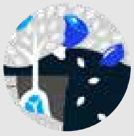
Arenas of innovation:
- Biomolecules
- Biosystems
- Biomachine interfaces

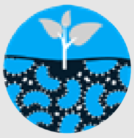
Transformational capabilities:
- Increased control and precision
- Enhanced ability to engineer and reprogram human and non-human organisms
- Increased throughput and productivity of R&D
- Growing potential for interfaces between biological systems and computers

Agriculture, aquaculture, and food


Selective breeding of animals and plants


CRISPR genetic engineering of plants


Growth of plant-based protein and lab-grown meat

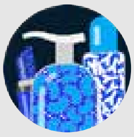

Microbiome data to optimize agricultural inputs

Arenas of innovation:
- Biomolecules
- Biosystems

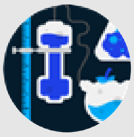
Transformational capabilities:
- Biological means for physical inputs
- Increased control and precision
- Enhanced ability to engineer and reprogram human and non-human organisms
- Increasing throughput and productivity of R&D

Consumer products and services


DTC genetic testing


Microbiome-based beauty products

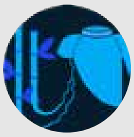

Genetically engineered pets


Personalized offering of health, nutrition, and fitness based on omics data

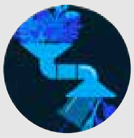
Arenas of innovation:
- Biomolecules
- Biosystems
- Biomachine interfaces

Transformational capabilities:
- Increased control and precision
- Growing potential for interfaces between biological systems and computers

Materials, chemicals, and energy


Development of new bioroutes for fabrics and dyes


Improvement of existing fermentation processes for industrial enzymes


Development of novel materials such as biopolymers


Extraction of raw materials using microbes

Arenas of innovation:
- Biomolecules
- Biosystems

Transformational capabilities:
- Biological means for physical inputs
- Enhanced ability to engineer and reprogram human and non-human organisms
- Increasing throughput and productivity of R&D

… for broad impact

Annual potential direct economic impact in 2030-40[1], $ trillion (% of total impact)	**Spillovers to upstream, downstream, and ancillary sectors** (examples)	**Shifting value chains and adapting business strategies** (examples)
Human health and performance 0.5–1.3 (35%)	Health insurance (eg, better prediction of risk and treatment outcomes) Ancillary services (eg, infrastructure required for storage and movement of cell therapies)	Spread of point-of-care diagnostics (eg, gene sequencing for cystic fibrosis) could decentralize care Pharmaceutical companies adapt business models in response to therapies that cure rather than treat over a lifetime
Agriculture, aquaculture, and food 0.8–1.2 (36%)	Food retailing and restaurants (eg, food with new properties like plant-based and cultured protein) Real estate (eg, reduction in land use because of more efficient agriculture, lab-grown meat) Transport and logistic players adjust to produce with new properties (eg, longer shelf life, ability to grow in new geographic regions) Environment (eg, meat production with smaller carbon footprint)	Transformation of meat value chain from: animals bred, fed, slaughtered, processed, and distributed → tissue sampling, media production, and live-tissue cultivation of cells into meat Consolidation of value chain as single player can do many steps in the value chain Emergence of business model selling yield goals instead of products such as bags of seed or pesticides
Consumer products and services 0.2–0.8 (19%)	Health insurance (eg, better prediction of risk based on consumer DTC genetic tests) Food (eg, change in demand driven by personalized diet plans) Healthcare (eg, DTC tests require more support from genetic counselors)	Movement up the value chain (eg, DTC testing company developing clinical products and services) New ways to monetize data (eg, companies selling consumer data to pharmaceutical companies for R&D purposes)
Materials, chemicals, and energy 0.2–0.3 (8%)	Fashion and cosmetics (eg, materials made more sustainably, such as nylon made from microbes rather than petrochemicals) Electronics (eg, biology-based optical film for displays) Consumer (eg, novel materials that improve quality of life for consumers)	Compressed value chain (eg, design, manufacturing, and customization of physical inputs in one place) Formation of platform-based companies serving clients across sectors

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1. Figures may not sum to 100% because of rounding. These impact estimates include direct economic impact across arenas of innovation. They are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation. % of total impact is based on the midpoint of our estimated range of annual potential direct economic impact.

Source: McKinsey Global Institute analysis

The total economic impact will likely be larger than the direct impact of the use cases we have identified and assessed

The direct potential impact estimated across the domains may be only a small portion of the potential scale of impact. Even in the near term, the impact could be larger, as new scientific breakthroughs emerge and as the direct impact we note above starts to have knock-on effects or spills over to other sectors. More broadly, the impact could radiate out to almost every sector of the economy, with effects on society and the environment. For instance, the visible pipeline of applications we sized in the human health domain is just a fraction of the full potential: as noted, between 1 and 3 percent of the current total global burden of disease could be reduced in the next ten to 20 years from just the use cases we examined—roughly the size of eliminating the global disease burden of lung cancer, breast cancer, and prostate cancer combined. While this near-term impact is rather significant, it is only a fraction of the transformational change that may be achievable. Many factors will shape the full extent of impact and the ability to capture as much of the full potential as possible; they include funding for basic science and treatments that pass clinical trials and are commercially viable alternatives to existing therapies.

The total economic impact could be larger than our direct sizing for a number of reasons:

— **Unassessed use cases.** Our library of about 400 use cases, while extensive, is not exhaustive. We acknowledge that there are many use cases being developed in private labs or in the defense industry, where developments remain confidential for commercial or national security reasons.

— **Faster and higher adoption.** Several factors could accelerate adoption of scientific advances. Companies could help speed up time to market and adoption of some applications by working with the scientific community, for example focusing on scientific advances and technologies that are likely to have the most impact, investing in them, and partnering with innovative startups. In addition to adoption speed, adoption peaks could be higher due to factors such as shifting product features, customer preferences, and lower prices. One example of this potential is higher or faster adoption of currently expensive therapies (for instance, CAR T-cell therapy for cancer) due to broader insurance coverage or lower prices.[29]

— **Knock-on economic effects.** The impact of some applications could in turn have knock-on effects for the broader economy. For example, improved health could mean that people lead longer and more productive lives; this in turn means that retirement ages may rise, demand for eldercare delivered in the home may rise, and social security and pensions may need to adapt. Alternative proteins are another example: if they replace some meat production, land now dedicated to grazing could be repurposed for conservation efforts or new commercial uses.

— **Impacts on upstream, downstream, and ancillary players.** After a first wave of change in the domains directly affected by bio innovations, a second wave may spill over to adjacent sectors or firms, transforming value chains and encouraging new business models and players. For example, applications in agriculture, aquaculture, and food could affect food retailing. Numerous fast-food chains have announced deals with plant-based meat-substitute producers to offer vegetarian and vegan versions of popular menu items. Logistics and transportation players may adapt to genetically engineered produce being able to be kept fresh for far longer even without being refrigerated, and to increased demand for alternative proteins.

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[29] CAR T-cell (chimeric antigen receptor T-cell). CAR T-cells are genetically engineered T-cells that express artificial chimeric antigen receptors on their surface. These engineered T-cells enable a patient's own immune system to identify and destroy targeted cells.

— **Existing scientific breakthroughs spur more breakthroughs.** Some innovations have the ability to generate more breakthroughs, by helping to improve existing products and processes or by inventing and implementing new ones. For example, the Human Genome Project initially set out to determine a map of the human genome. In doing so, the project was instrumental in pushing the development of high-throughput technologies for preparing, mapping, and sequencing DNA. The improved ability to sequence DNA has, in turn, led to sequencing of the genomes of microbes, plants, and animals, which has advanced many fields of science, including microbiology, virology, infectious disease, and plant biology. In addition, new biology and new technologies brought about by the Human Genome Project have enabled many other large-scale research initiatives to go forward. Examples include the Encyclopedia of DNA Elements research consortium (ENCODE), International HapMap Project, 1000 Genomes, Cancer Genome Anatomy Project, Human Microbiome Project, and Roadmap Epigenomics Project.[30]

— **More scientific breakthroughs enabling more commercial applications.** Biology research is continually developing, and scientific breakthroughs we haven't yet contemplated could provide a foundation for downstream commercial applications that may become available in the next few decades. For example, before the Human Genome Project, researchers knew the genetic basis of tens of disorders. Today, they know the basis of thousands of conditions. Genomics is thus helping transform medicine. More than 100 different drugs approved by the US Food and Drug Administration (FDA) are now packaged with instructions that tell doctors to test their patients for genetic variants linked to efficacy, dosages, or risky side effects.[31] Funding basic science or helping promising applications accelerate through research pipelines could directly influence the number of commercial applications in the future, beyond use cases we may have missed in our sizing.

In the longer term, every sector may be affected as bio innovation transforms profit pools, value chains, and business models. In the years ahead, if you are not using biology to make products, you will very likely be consuming products made that way. The impact could go much further, with biology potentially being used to address some of the great challenges of our time.

As an example, climate change is a key area in which biology could play a role. By 2040 to 2050, the direct applications we sized could reduce annual average man-made GHG emissions by 7 to 9 percent from 2018 emissions levels. This is the equivalent of up to eight times the total carbon dioxide (CO_2) emissions of the global airline industry in 2018.[32] Applications such as a shift toward bioroutes for production and alternative proteins would be important contributors to reduced emissions. The knock-on effects could alleviate pressure on cropland and reduce deforestation.

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[30] Leroy Hood and Lee Rowen, "The Human Genome Project: Big science transforms biology and medicine," *Genome Medicine*, September 2013, Volume 5, Number 79; and "Spinoff projects related to the Human Genome Project," Human Genome Project Information Archive 1990–2003, https://web.ornl.gov/sci/techresources/Human_Genome/research/spinoffs.shtml. Epigenomics is the study of the epigenome, specifically epigenetic modifications that affect gene expression such as DNA methylation and histone modification. This can direct such actions as turning genes on or off, and controlling the production of proteins in particular cells.

[31] Susan Young Rojahn, "A decade of advances since the Human Genome Project," *MIT Technology Review*, April 12, 2013.

[32] Total GHG emissions, including from land use, land-use change, and forestry, were 75.9 $GtCO_2e$ in 2018, according to the UN's *Emissions gap report 2019*. For the purposes of policy discussion and target setting, greenhouse gases are generally quantified by global warming potential (GWP), a measure of how much energy the emissions of one ton of gas will absorb during a given period, relative to the emissions of one ton of carbon dioxide. GWP is calculated for a specific time span, most commonly 100 years. But the lifetime for each greenhouse gas is different. Methane lasts in the atmosphere only for approximately 12 years, so its GWP will differ depending on a given time span. One ton of methane has 28 times the effect of one ton of carbon dioxide when measured at a 100-year GWP but 84 times the effect at a 20-year GWP. Given the importance of action and the short-term potential gain of reducing agriculture's methane emissions, our primary analysis is based on 20-year GWP values. The global CO_2 emissions of the airline industry were about 0.9 gigaton in 2018. *ICAO global environmental trends – present and future aircraft noise and emissions*, International Civil Aviation Organization working paper number 54, May 7, 2019. Also see *Understanding global warming potentials*, US Environmental Protection Agency; and *Climate change 2013: The physical science basis*, Intergovernmental Panel on Climate Change, 2013.

Biology could also make a significant contribution to efforts to increase food security around the world, addressing hunger and malnutrition. The Bill & Melinda Gates Foundation, for example, suggests that by using improved fertilizer and more productive crops such as genetically engineered varieties, African farmers could theoretically double their yields.[33]

However, for all this potential, biological applications will not likely be a panacea for societal ills and challenges. In many ways, their societal effects proceed unevenly, in part driven by level of access to these innovations across socioeconomic groups or nations. And, critically, the risks of biology will need to be addressed and satisfactorily mitigated if biology is to realize its potential.

Bio innovation carries profound and unique risks and issues

Profound risks accompany this surge of innovation in biology. Get it right and the benefits could be significant; get it wrong and disastrous consequences could ensue at the population level. These risks introduce a unique set of considerations which, if not managed properly, could potentially outweigh the promised benefits:

— **Biology is self-replicating, is self-sustaining, and does not respect jurisdictional boundaries.** For example, new genetically engineered gene drives applied to the vectors that spread disease (mosquitoes in the case of malaria) could have enormous health benefits, but they can be difficult to control and can potentially do permanent damage to ecosystems. There are also no boundaries for the spread of unintended consequences.

— **The interconnected nature of biology can increase the potential for unintended consequences.** Biology is highly interconnected; changes to one part of a system can have cascading effects and unintended consequences across entire ecosystems or species. Examples include planting a genetically engineered crop that could result in unintended effects on the species or broader ecosystem. Gene editing could also have unintended or "off target" effects. For instance, even in successful gene editing, "off-target" mutations beyond those intended have been observed for all classes of genome editing tools used to date, including CRISPR.[34]

— **Low barriers to entry open the door to potential misuse with potentially fatal consequences.** Unlike nuclear materials, some biological technologies are relatively cheap and accessible. A thriving community of "biohackers" practices gene editing today in community labs or even at home. Commercial kits to perform CRISPR gene editing are sold on the internet. This activity might affect only the individuals biohacking their own bodies, but there are broader risks, for example if individuals are able to create and unleash a virus. Beyond such risks, we could see increased competition between companies, particularly in consumer applications, which could lead to overhyped marketing. Competition to bring biologically based products and services to market in some cases has led to commercialization before the relevant science is fully tested and established, which could mislead consumers, erode trust, or even compromise health and safety.

— **Differing value systems make it hard to forge consensus, including on life-and-death issues.** At the heart of many of these risks is the challenge of coordination across value systems—at the individual, cultural, and national levels. Technical and scientific issues, such as embryo editing, quickly become moral questions, and often, decisions are expressions of one's value system. Beyond the many risks are significant ethical questions that exceed the scope of this report. Is the ability to edit out disabilities before

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[33] Elizabeth Lopatto, *Can GMOs end hunger in Africa?*, The Verge, February 2015.

[34] Yong Cheng and Shengdar Q. Tsai, "Illuminating the genome-wide activity of genome editors for safe and effective therapeutics," *Genome Biology*, December 2018, Volume 19; Dana Carroll, "Collateral damage: Benchmarking off-target effects in genome editing," *Genome Biology*, June 2019, Volume 20; and *Nature Medicine*, "Editorial: Keep off-target effects in focus," August 2018, Volume 24.

birth “playing God”? Is it acceptable to edit an embryo to prevent sickle cell anemia, but wrong to choose a baby’s skin or eye color? Sustained efforts and new approaches to engagement, oversight, regulation, and safeguarding are needed to manage such risks. These will need to take into account societal norms and acceptance that are often shaped by religious, cultural, and historical values and can vary widely between countries. The challenge of cooperation and coordination of value systems across cultures and jurisdictions is no easy task, particularly when advances in these scientific domains could be seen as a unique competitive advantage for businesses or economies.

— **Privacy and consent issues are fundamental.** Concerns about personal privacy and consent are rife, given that the cornerstone of biological advances is data mined from our bodies and brains. In the United States, using the results of only 1.28 million DTC genetic tests, it was possible to access material from open databases and identify about 60 percent of Americans with European ancestry from a DNA sample as of late 2018, prompting some DTC companies to tighten up the availability of such data.[35] As applications of biomachine interfaces and, in particular, brain-machine interfaces spread, the amount of data harvested from brains will most likely increase. When and how do individuals give consent to what data are gathered and how they are used? Is the science available that can differentiate between thoughts that an individual wants and does not want to share?

— **Unequal access could perpetuate socioeconomic disparity, with potentially regressive effects.** Biological advances and their commercial applications may not be accessible to all in equal measure, thereby exacerbating socioeconomic disparity. At the country level, developments are advancing quickest and most broadly in relatively rich nations. Our analysis finds that countries with high rankings on the Institute for Health Metrics and Evaluation’s (IHME) socio-demographic index account for roughly 30 percent of today’s global disease burden but could gain about 70 percent of the total share of reduction in the global disease burden from bio innovations.[36] Within countries, access to some beneficial biological applications may be cost prohibitive and thus available only to the wealthy, like cellular and gene therapies today. Furthermore, the very nature of these applications to edit “less desirable” traits could lead to outcomes that are regressive and disenfranchise marginalized groups. Examples of this could include genome editing for traits related to blindness or dwarfism, which are tied to the ongoing discussion of so-called ableism—that is, whether the aim of restoring a sense inherently marginalizes communities that do not see the lack of that sense as a disability.

These risks demand a considered response and potentially new approaches. In past waves of technological change, regulation has emerged in response to innovations; in biology, there is a strong argument for a proactive approach. As far back as 1975, prominent scientists, lawyers, and medics gathered in California to draw up voluntary guidelines to ensure the safety of recombinant DNA technology.[37] The scientific communities in other fields, such as nuclear physics and AI, are also grappling with analogous issues, and there could be room for cross-disciplinary collaboration. Regulation will be important, but so too will oversight and monitoring of science even as it develops, as well as safeguards that scientists build into new biological technologies.

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[35] Yaniv Erlich et al., “Identity inference of genomic data using long-range familial searches,” *Science*, November 2018, Volume 362, Issue 6415.

[36] The socio-demographic index is a development classification system specific to the Institute for Health Metrics and Evaluation (IHME) based on metrics such as per capita income and average years of schooling. Figures given are based on the IHME Global Burden of Disease 2017.

[37] Recombinant DNA molecules are formed by combining genetic material from multiple sources to create sequences not found in the genome (molecular cloning, for instance). See Paul Berg et al., “Summary statement of the Asilomar Conference on recombinant DNA molecules,” *Proceedings of the National Academy of Sciences*, June 1975, Volume 72, Number 6.

National responses will not be sufficient, because biology doesn't respect borders—as the world experienced firsthand with the rapid spread of the COVID-19 infection around the globe. Moreover, we can already see very different regulatory responses reflecting a world with many different value systems. Some countries take a cautious view of frontier innovation, including embryo editing and genetic engineering of food crops; others take a permissive view. Lighter-touch regulation may deliver—or be seen to deliver—competitive advantage compared with a more restrictive approach. Global cooperation and coordination could help level the playing field but will be difficult to achieve when disparate value systems exist.

Science is the starting point—applications need to be commercialized and diffused responsibly to deliver beneficial impact at scale

The journey from the lab to adoption has three broad stages—scientific research, commercialization, and diffusion—that bleed into each other in a continuous evolution. For biological applications to diffuse and deliver beneficial impact responsibly and at scale, six factors are relevant that determine whether adoption occurs and how long that takes. The first— investing in scientific research—is germane in the first stage. Four factors—value propositions, business models, go to market, and operational scalability—are key for the second and third stages, commercialization and diffusion. The sixth relates to risk and mechanisms for governing the use of applications; this is vital in all three stages:

- **Investment in scientific research.** Funding, tools, talent, and access to data are necessary and powerful elements of the investment needed to enable scientists to be successful. It tends to take years of research and sizable investment in these capabilities to get an idea to the point at which a product or service is scientifically feasible.[38] To give an idea of the financial investment needed, the Human Genome Project involved $3 billion in investment. Applications are moving along fastest in higher-income economies where investment money is available. The development of new tools and technologies in biological sciences has extended the capabilities of research. For instance, CRISPR was a major leap forward in the ability to edit genes. Expanding and ever-cheaper computing power has enabled the rapid development of bioinformatics.[39] Ensuring that sufficient numbers of skilled scientists are trained is vital. Finally, investment to ensure that scientists have access to the data on which advances depend is crucial. The development of annotated and accessible databases such as the Human Genome Project, GenBank, and UniProt has played a significant enabling role in biological advances.

- **Four factors play a role in commercialization and diffusion.** Once an application is scientifically feasible, other factors will determine the journey from lab to market to wide adoption and diffusion. We have identified four key factors, the first of which is whether a new biology-based product or service offers a value proposition to potential end users. Innovations need to compete with existing products not only on cost but also by offering higher quality or new properties or, indeed, by meeting a need not fulfilled by existing offerings. Creating a value proposition is not easy. Many potential buyers of biology-based products are in industries with low margins such as energy and agriculture, and established products or methods of production have had years to develop ways to improve efficiency. Even when they start diffusing, some biology-based innovations remain costly. Although the cost is now falling rapidly, the cost to produce the first lab-grown hamburger was more than $300,000.[40]

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[38] We define scientific feasibility as experimental success in the target population (for instance, in the case of human health, success in humans rather than mice models). For applications where we could not identify proof of concept in academia or industry, we assessed feasibility using sector-specific analogs and expert interviews that estimate how far away scientific feasibility might be.

[39] This is a hybrid science that links biological data with techniques for information storage, distribution, and analysis to support multiple areas of research, including biomedicine.

[40] Neil Stephens, Alexandra E. Sexton, and Clemens Driessen, "Making sense of making meat: Key moments on the first 20 years of tissue engineering muscle to make food," *Frontiers in Sustainable Food Systems*, July 10, 2019; and Muhammad Sajid Arshad et al., "Tissue engineering approaches to develop cultured meat from cells: A mini review," *Cogent Food & Agriculture*, 2017, Volume 3, Issue 1.

- **The second factor is whether business models are suitable in what may be a fast-changing landscape, as in most waves of innovation.** New models, such as bionative companies that combine expertise in biology, chemistry, data science, and automation, may be needed. The third factor is ensuring that a new product or service effectively hits the right potential customers, with go-to-market elements, including pricing, sales, and marketing. A fourth vital factor is the ability to scale up operations; necessary aspects include having the right infrastructure, processes, supply chain, and talent. New bio-based fermentation techniques can build on considerable existing fermentation capacity, but more will be needed. Healthcare capacity will need to adapt and grow to disseminate medical innovations. For instance, with CAR T-cells now being administered to a growing number of patients in hospitals and treatment centers, sufficient infrastructure for manufacturing and delivering the cells is necessary.[41] Again, sufficient talent is needed. Genetic counselors to help patients and the public understand and interpret the results of genetic tests are already in short supply.[42] In the United States, for instance, there were approximately 5,000 certified genetic counselors in 2019.[43] Yet 26 million consumers have taken an at-home genetic test.

- **Risk and mechanisms governing use.** Given the profound and unique risks accompanying bio innovation, mechanisms governing use, including broad acceptance from society and regulation, are key both in the first stage and also as the science commercializes and diffuses. Even if an application is scientifically feasible and the economics are favorable, end users and other stakeholders must want to use it, sometimes accepting some risk. As an illustration, it took nearly 20 years from the production of the first strain of Golden Rice—fortified with vitamin A—to be approved for use in 2019 in the Philippines, the first country with many people suffering from vitamin A deficiency to approve Golden Rice.[44] Regulators delayed in the face of persistent opposition to GMOs.[45] Our research finds that about 70 percent of the total potential impact could hinge on consumer, societal, and regulatory acceptance, based on an analysis of areas where regulations exist today in major economies.[46]

The pace and extent of adoption of bio innovations vary significantly depending on the application

The pace and extent of adoption will vary enormously depending on the application and the domain (Exhibit E6). Some applications, including using new bioroutes to manufacture drugs, are already showing robust signs of early commercial adoption. Others such as CAR T-cell therapy for cancer have recently become commercially viable at the time of writing in 2020, meaning adoption is at an early stage and could increase rapidly over the coming decade. Still others, such as using genetically engineered plants to sequester CO_2, show promise in scientific research, but commercial viability and adoption by farmers or other buyers are likely further out.

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[41] Jacob Bell, *Car-T ups challenges in pharma supply chain*, Biopharma Dive, April 23, 2018.

[42] J. M. Hoskovec et al., "Projecting the supply and demand for certified genetic counselors: A workforce study," *Journal of Genetic Counseling*, February 2018, Volume 1.

[43] *Genetic counselor workforce initiatives*, National Society of Genetic Counselors.

[44] Prior to approval in Philippines, Golden Rice was registered as safe in Australia, Canada, New Zealand, and the United States, all countries with few vitamin A deficiency problems. See Michael Le Page, "GM golden rice gets landmark safety approval in the Philippines," *New Scientist*, December 31, 2019. This is based on World Health Organization data on the prevalence of vitamin-A deficiency in pregnant women and preschool-age children from 1995 to 2005. See WHO, *Global prevalence of vitamin A deficiency in populations at risk 1995–2005*, WHO Global Database on Vitamin A Deficiency, 2009.

[45] Jesse Hirsch, "Golden Rice: A brief timeline of the world's most controversial grain," *Modern Farmer*, August 27, 2013; *Philippines approves nutritionally-enhanced GMO Golden Rice for human consumption*, Genetic Literacy Project, December 18, 2019.

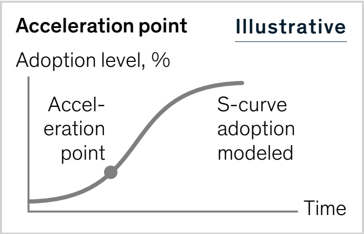
[46] We examined existing regulations and their applicability to sized applications. Applications were also considered at stake if they relate to highly sensitive topics in academic circles, such as embryo editing and bioweapons. Our analysis is as of September 2019.

Exhibit E6

Among applications assessed, adoption timing varies.

Estimated time horizon of acceleration point of use cases across domains
The acceleration point is when adoption starts to experience rapid growth[1]

Example use cases **Not exhaustive**	**Existing** Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
Human health and performance[2]	Carrier screening Noninvasive prenatal testing	CAR T-cell therapies for liquid tumors Liquid biopsy	Gene drives to reduce vector-borne diseases CAR T-cell therapies for solid tumors	Transplantable organs produced from stem cells Embryo editing for medical purposes (eg, via CRISPR)
Agriculture, aquaculture, and food[3]	Marker-assisted breeding (crops and animals used for food) Genetic tracing of food origin, safety, and authenticity (eg, allergens, species, pathogens)	Plant-based proteins Crop microbiome diagnostics and probiotic treatments	Cultured meat Genetically engineered animals—faster growth	Genetically engineered crops—faster growth through enhanced photosynthesis
Consumer products and services[4]	DTC genetic testing—ancestry	Personalized meal services based on genetic and microbiome profile DTC genetic testing—personal insights about health and lifestyle	Biosensors for monitoring of personal health, nutrition, and fitness based on omics data	Gene therapy—skin aging
Materials, chemicals, and energy[5]	New bioroutes for drug manufacturing (eg, peptides)	Novel materials—biopesticides/biofertilizers (eg, RNAi pesticides) Improved existing fermentation processes—food and feed ingredients (eg, amino acids, organic acids)	Novel materials—biopolymers (eg, PLA, PET)	Biosolar cells and biobatteries
Other applications	DNA sequencing for forensics		Biosequestration of CO_2 Bioremediation for pollution	


Acceleration point **Illustrative**

1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.
2. Applications in the human health and performance domain include innovations to reduce disease burden at the individual and population levels, anti-aging treatments that extend life span, reproductive health (eg, carrier screening) applications, and innovations in drug development and manufacturing. See chapter 6.1 for the full list of applications that we sized in this domain.
3. Applications in the agriculture, aquaculture, and food domain include applications related to plants and animals for food purposes, food production, food transportation, and food storage. See chapter 6.2 for the full list of applications that we sized in this domain.
4. Applications in the consumer products and services domain include direct-to-consumer genetic testing, beauty and personal care, wellness (eg, fitness), and pets. We categorize wellness, nutrition, and fitness under consumer rather than health, because they do not directly alleviate the global disease burden or are elective or for adult enhancement, such as hair loss or cosmetics. While some of these applications could have indirect impact on the disease burden, such as fitness wearables, they are not direct treatments or therapies. See chapter 6.3 for the full list of applications that we sized in this domain.
5. Applications in the materials, chemicals, and energy domain include innovations related to production of materials (eg, improved fermentation process, new bio-routes, or novel materials), and energy production and storage. See chapter 6.4 for the full list of applications that we sized in this domain.

Source: McKinsey Global Institute analysis

Innovators, businesses, governments, and individuals need to strike a balance that enables potential to be captured while managing risks

Innovators, businesses, governments, and individuals need to become literate in biology, cognizant of the benefits of innovations as well as their risks, and how to strike the right balance between the two. The choices made today, and in the years ahead, will influence not only the path of biological science, but also the size and scope of its benefits for economies, societies, and the planet.

— **Innovators.** The scientists and researchers pioneering biological breakthroughs, and the developers and innovators who turn feasible science into commercially viable products, need to consider the opportunities and risks associated with their work. Peer review is a powerful internal governing mechanism to ensure that research is accurate and well grounded, but scientists cannot operate in a vacuum. Rather, they need to play a consistent and effective oversight role. They have a long track record of doing so. In 1975, prominent scientists, lawyers, and medical professionals gathered at the Asilomar Conference in California to draw up voluntary guidelines to ensure the safety of recombinant DNA technology, for instance.[47]

— **Businesses.** Businesses should consider how to take advantage of bio innovation, including adapting strategies. Companies operating in virtually every sector of the economy could be affected by bio innovations as applications in one domain have knock-on effects on upstream, downstream and adjacent sectors. In the case of applications in agriculture, aquaculture, and food, there will be spillover into food retailing and transportation, for instance. Moreover, entire value chains could be transformed. In the case of materials, for instance, with a shift from plastic to bio-based plastic packaging increasingly desired by consumers, the packaging industry could look very different. The meat value chain is another case in point. In the traditional meat production value chain, animals are bred, fed, slaughtered (fished), and processed prior to distribution, while the value chain for cultured meat is highly compressed, involving only tissue sampling, media production, and live-tissue cultivation of cells into meat—often done by the same company (Exhibit E7).[48]

Many companies will likely need to adapt their business strategies. Given the uncertainty and evidently varied timing of adoption for different applications, companies should consider a portfolio-based approach toward investments in bio innovation that embraces applications that could become commercially viable in the relatively short term, and those that could deliver impact further out. By its nature, bio innovation is cross-discipline—embracing not only biological science, but also computing, AI, data analytics, and engineering. As such, it is unlikely that any business existing today can go it alone. Therefore, it's important to master the confluence of disciplines in bio innovation with the right mix of talent and collaborations. Although large companies could develop the full range of necessary capabilities in-house, it is likely to be quicker and more effective to "buy in" what they need through mergers and acquisitions, and partnerships. Small companies specializing in particular scientific fields are already collaborating with large incumbents with the market clout to commercialize at scale. As in the Digital Revolution, companies interested in the opportunity of bio innovation should consider platform-based business models that can seize cross-sector opportunities, reduce marginal costs, and drive combinatorial innovation by leveraging growing biological data. There are already platforms that offer farm-management systems and cloud-based platforms that analyze huge amounts of genomic data to inform breeding decisions.[49] Among other aspects

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[47] Recombinant DNA molecules are formed by combining genetic material from multiple sources to create sequences not found in the genome (molecular cloning, for instance). See Paul Berg et al., "Summary statement of the Asilomar Conference on recombinant DNA molecules," *Proceedings of the National Academy of Sciences*, June 1975, Volume 72, Number 6.

[48] Cultured meat is produced by the in vitro cultivation of animal cells.

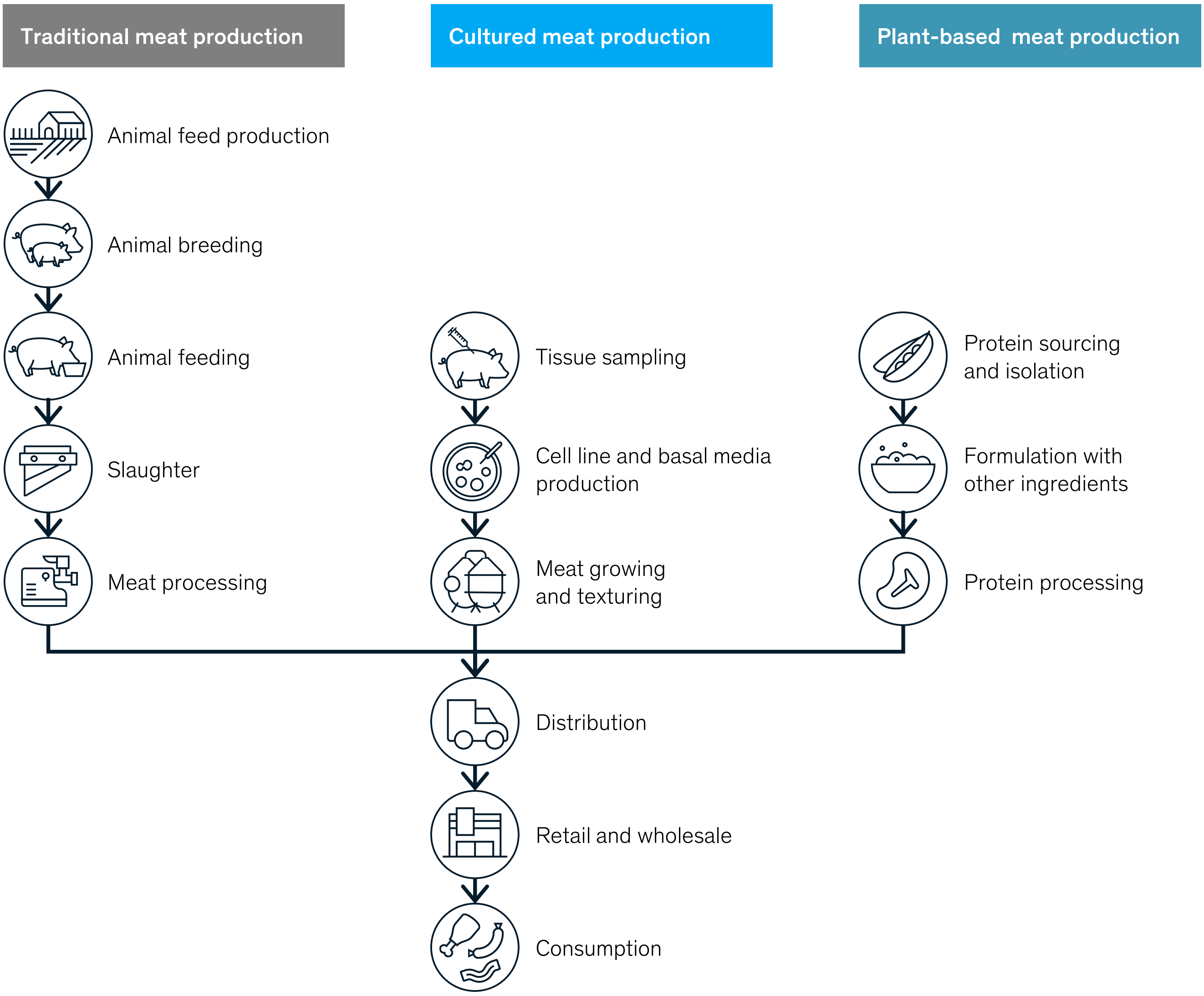
[49] Geoffrey Carr, "Factory fresh," *Economist Technology Quarterly: The Future of Agriculture*, June 2016; and BASF and NRGene, *BASF and NRGene collaborate to accelerate crop breeding*, October 29, 2019.

to consider are the range of opportunities for more personalized and precise offerings enabled by growing amounts of biological data, and innovative revenue models that could help accelerate diffusion. Subscription-based offerings to generate revenue are becoming more common in personalized products and services based on genome and microbiome profiles.

Exhibit E7

The meat value chain is shifting.

Traditional meat production vs cultured meat and plant-based meat production



Source: McKinsey Global Institute analysis

— **Civil society, governments, and policy makers need to inform themselves about biological advances and to provide thoughtful guidance.** Several governments, including those of China, the United Kingdom, and the United States, published strategic plans and goals intended to catalyze innovation and capture its benefits. However, innovation needs to be balanced by mechanisms to govern use and misuse; whether existing professional and regulatory mechanisms are fit for purpose must be considered. This analysis suggests that in the next decade, more than 50 percent of the total potential impact could hinge on consumer, societal, and regulatory acceptance, rising to about

70 percent over the next two decades.[50] Effective mechanisms to govern use, such as societal norms or regulations, will be needed to persuade society that innovations that bring benefits but may be risky and cause discomfort are being pursued safely. Today, policies to govern use vary significantly among countries with different value systems. Cross-jurisdictional cooperation is not extensive, as observed in the largely national (and subnational) responses in spring 2020 to the COVID-19 pandemic.

- **Individuals and consumers may be pivotal to the adoption path of biological advances.** As observed, individual attitudes toward different types of bio innovation can shape the public dialogue, societal norms, regulation, and therefore the pace and extent of adoption. To contribute effectively to what can be controversial debates (consider embryo editing as an example), individuals need to seek to understand the benefits versus the risks. They also need to appreciate that there are personal trade-offs. DTC testing, for instance, provides individuals with potentially valuable insights into the probability of contracting certain diseases, but mining that information may compromise their privacy.

The current wave of innovation in biological sciences, combined with advances in data, analytics, and digitization, has been decades in the making. It builds on 50 years or more of scientific breakthroughs (see illustration, “A partial timeline of accelerating breakthroughs in biological sciences”). The Bio Revolution goes far beyond treating disease and into virtually every sector of the economy. Scientists in conjunction with forward-thinking companies are now harnessing the power of nature to solve pressing problems in medicine and agriculture, and, in some areas, forging innovative solutions that could mitigate pressure on the environment and help tackle climate change. The serious, and potentially irreversible, risks inherent in biology need to be fully acknowledged and directly addressed. The choices stakeholders make today and in the years ahead will determine whether what is shaping up as a Bio Revolution delivers on its considerable promise—and in a way that is safe and equitable for humanity and sustainable for the planet.

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[50] Analysis includes examination of existing regulations in the different countries and their applicability to sized applications. Applications are also considered at stake if they are related to highly sensitive topics in academic circles, such as embryo editing and bioweapons. Analysis of existing regulations as of September 2019.

A partial timeline of accelerating breakthroughs in biological sciences

(continued on next page)

1865

Mendel's principles of inheritance for traits published

1881

Nucleotides, DNA and RNA building blocks, discovered

1935

The last of 20 common amino acids discovered

1951

Henrietta Lacks's cancer cells became the first human "cell line" to be established in culture

1953

DNA's double helix structure elucidated by Crick, Watson, Wilkins, and Franklin

1958

Francis Crick's "central dogma" describing how cellular information flows from DNA to RNA to proteins published

The first 3-D structure of a protein, myoglobin, reported at the atomic level

1998

Human embryonic stem cells isolated

1999

First lab-grown complex internal organ (bladder sacs) transplanted into humans

2000

First super-resolution microscopy developed enabling observation of many sub-cellular structures and processes previously elusive to light microscopy

2002

Quantitative time-lapse fluorescence microscopy in single cells demonstrated cell-to-cell variability in gene expression in genetically identical cells

2003

Human Genome Project declared completed

2004

Concept of mimicking organ-level function inside a microfluidic chip (organ-on-a-chip) published

2006

Techniques for reprogramming adult cells into pluripotent stem cells published

23andMe became the first company to offer DNA testing for ancestry

2007

Human Microbiome Project (United States) launched

2008

RNA-seq, a high-throughput method to study transcriptomics, developed and applied to study transcriptome of yeast

2011

FDA approved first immune checkpoint inhibitor, Ipilimumab, for cancer immunotherapies

2012

The first method for characterizing the gene expressions of individual cells using single-cell RNA-Seq became feasible at large scale

2013

Scientists deleted existing memories and "incepted" false ones in mice

First reports on using CRISPR gene editing in mammals published

BRAIN Initiative (United States) and Human Brain Project (European Union) launched to map the brain

McKinsey
Global Institute

1966

Genetic code for all 20 amino acids deciphered

1972

First recombinant DNA molecules generated

1977

World's first IVF baby, Louise Brown, born

The technique for Sanger sequencing—a breakthrough in DNA sequencing—is published

1979

World Health Organization declared smallpox eradicated

1982

US Food and Drug Administration (FDA) approved first drug using recombinant DNA technology (recombinant human insulin)

1984

siRNA enabling gene regulation at the RNA level discovered

1985

Polymerase chain reaction (PCR) enabling large-scale rapid copies of DNA invented

1988

First person, Colin Pitchfork, convicted of murder using DNA evidence

1990

First successful gene therapy (for adenosine deaminase deficiency) clinical trial

Human Genome Project launched

1993

High-throughput characterization of entire sets of proteins made possible by mass spectrometer

1994

First genetically engineered crop, Calgene's Flavr Savr tomato, approved for commercial production

Green fluorescent protein cloned

Early high-throughput use of microfluidics in biology for DNA sequencing

1996

First mammal (Dolly the sheep) cloned from an adult somatic cell using nuclear transfer born

First Roundup Ready crops (GM soybeans resistant to Roundup) developed

2016

Designer proteins unlike anything found in nature created, enabling novel medicines and materials

Two monkeys subjected to a spinal-cord injury that paralyzed one leg regained ability to walk using a brain–spine interface

Human Cell Atlas Project launched to map all cells in the human body at a molecular level

2017

FDA approved the first CAR T-cell therapy for cancer

2018

Chinese scientist reported birth of first gene-edited babies

A new way to determine molecular structures of small organic compounds in minutes rather than days or weeks developed

Golden State Killer arrested on basis of DNA found at crime scenes that partly matched that of a relative on a genealogy website

2020

Pan-Cancer project completed the most comprehensive map of cancer genomes

Box E1

An April 2020 snapshot of early contributions by bio innovations in the fight against COVID-19

The rapid spread around the world in spring 2020 of a new coronavirus—SARS-CoV-2—imposed heavy health and economic costs.[1] While the impact of COVID-19 was still unfolding at the time of writing in April 2020, bio innovations had been deployed to aid the response. More needs to be done to cope effectively with pandemics of this nature, but here we share a snapshot of some of the contributions made by advances in biological science that we observed in the early days of this pandemic.

Identification. The full genome of SARS-CoV-2 was sequenced and published weeks after the novel coronavirus was identified. By comparison, it took several months to sequence and publish the SARS-CoV-1 virus that caused the SARS outbreak.[2]

Diagnosis. Advances in nucleic acid-based diagnostics have enabled more effective diagnosis. In the past decade, for instance, the continued miniaturization of reverse transcription polymerase chain reaction (RT-PCR) machines made the technology more accessible for use in the field.[3] The speed of the diagnostics also significantly improved with some labs able to produce results in 15 minutes.[4] However, the many challenges with diagnosis during the COVID-19 crisis also highlighted the fact that ample room remains for further improvement of diagnostics.

Vaccines. The speed and scale at which researchers launched efforts to develop a COVID-19 vaccine was remarkable. This agility was driven in large part by the public health urgency, but also reflected innovations such as faster and more versatile, nucleic-acid-based vaccine production and AI-powered R&D.[5] As of April 2020—around three months after SARS-CoV-2 was sequenced—more than 60 vaccines were in the preclinical stage and seven were in Phase 1 trials, although whether these efforts prove successful remained unclear. In contrast, it took more than a year after the Zika epidemic began in 2015 to start Phase 1 trials.[6]

Treatment. New capabilities assisted in developing new treatments for those infected. Genetically engineered animals were used to develop potential therapies, including using mice to produce monoclonal antibodies and cows to produce polyclonal antibodies.[7] Therapies using siRNA, RNAi, T-cells, and stem cells were also explored. Patient gene expression (mRNA) profiles were gathered into a biobank with the aim of using the repository to identify new therapies.[8] The efficacy of such treatments remained to be proven as of April 2020.

Epidemiology. Genomics was used to try to uncover population-level insights. In the case of SARS-CoV-2, its genome was regularly sequenced in different geographies and hotspots to look for mutations that could indicate its place of origin and transmission dynamics.[9]

More clearly needs to be done to improve our collective response to dangerous pandemics such as COVID-19. Bio innovations are ongoing, and the way we respond to future pandemics may look very different. For instance, in the future it may be possible to leverage emerging technologies such as AI-enabled epidemiology to predict outbreaks or use algorithms to predict the structure of proteins to enable faster drug discovery.[10]

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[1] Kevin Sneader and Shubham Singhal, *Beyond coronavirus: The path to the next normal*, McKinsey & Company, March 2020; and Sven Smit, Martin Hirt, Kevin Buehler, Susan Lund, Ezra Greenberg, and Arvind Govindarajan, *Safeguarding our lives and our livelihoods: The imperative of our time*, McKinsey & Company, March 2020.

[2] WHO Timeline – COVID-19, www.who.int/news-room/detail/27-04-2020-who-timeline---covid-19; and Severe Acute Respiratory Syndrome (SARS), notice, Centers for Disease Control and Prevention, www.cdc.gov/sars/lab/sequence.html.

[3] RT-PCR is a laboratory technique used to make large-scale copies of specific segments of DNA molecules rapidly and precisely outside the body from a mixture of DNA molecules.

[4] Jim Daley, “Here’s how coronavirus tests work—and who offers them,” *Scientific American*, March 27, 2020, updated April 6, 2020.

[5] Nicole Lurie et al., “Developing COVID-19 vaccines at pandemic speed,” *New England Journal of Medicine*, March 30, 2020, updated April 6, 2020.

[6] Alan D. T. Barrett, “Current status of Zika vaccine development: Zika vaccines advance into clinical evaluation,” *NPJ Vaccines*, June 2018, Volume 3.

[7] Monoclonal antibodies are man-made antibodies of predetermined specificity against targets made by identical immune cells derived from a unique parent cell.

[8] Small interfering RNA or siRNA is central to RNA interference. siRNA is a family of double-stranded non-coding RNA molecules, with typical lengths of 20 to 25 base pairs that regulate the expression of specific genes with complementary nucleotide sequences by degrading their mRNA transcripts, preventing translation. RNA interference (RNAi) is an evolutionarily conserved gene silencing technique in which specific genes can be regulated and suppressed at the RNA level. T-cells are lymphocyte immune cells that protect the body from pathogens and cancer cells.

[9] Niema Moshiri, *Here’s how scientists are tracking the genetic evolution of COVID-19*, The Conversation, April 6, 2020.

[10] One company is using a computer program to predict the 3D shape of proteins based on that protein’s amino acids. Predicting the structure makes it easier to design drug molecules that are more likely to bind to the protein. See Faris Gulamali, *AlphaFold algorithm predicts COVID-19 protein structures*, InfoQ, March 31, 2020.

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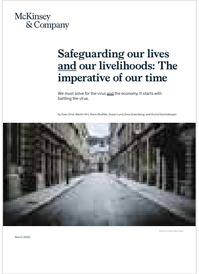

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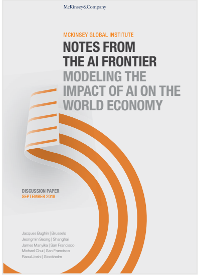

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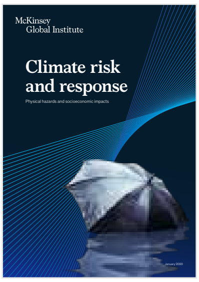

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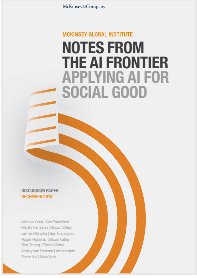

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