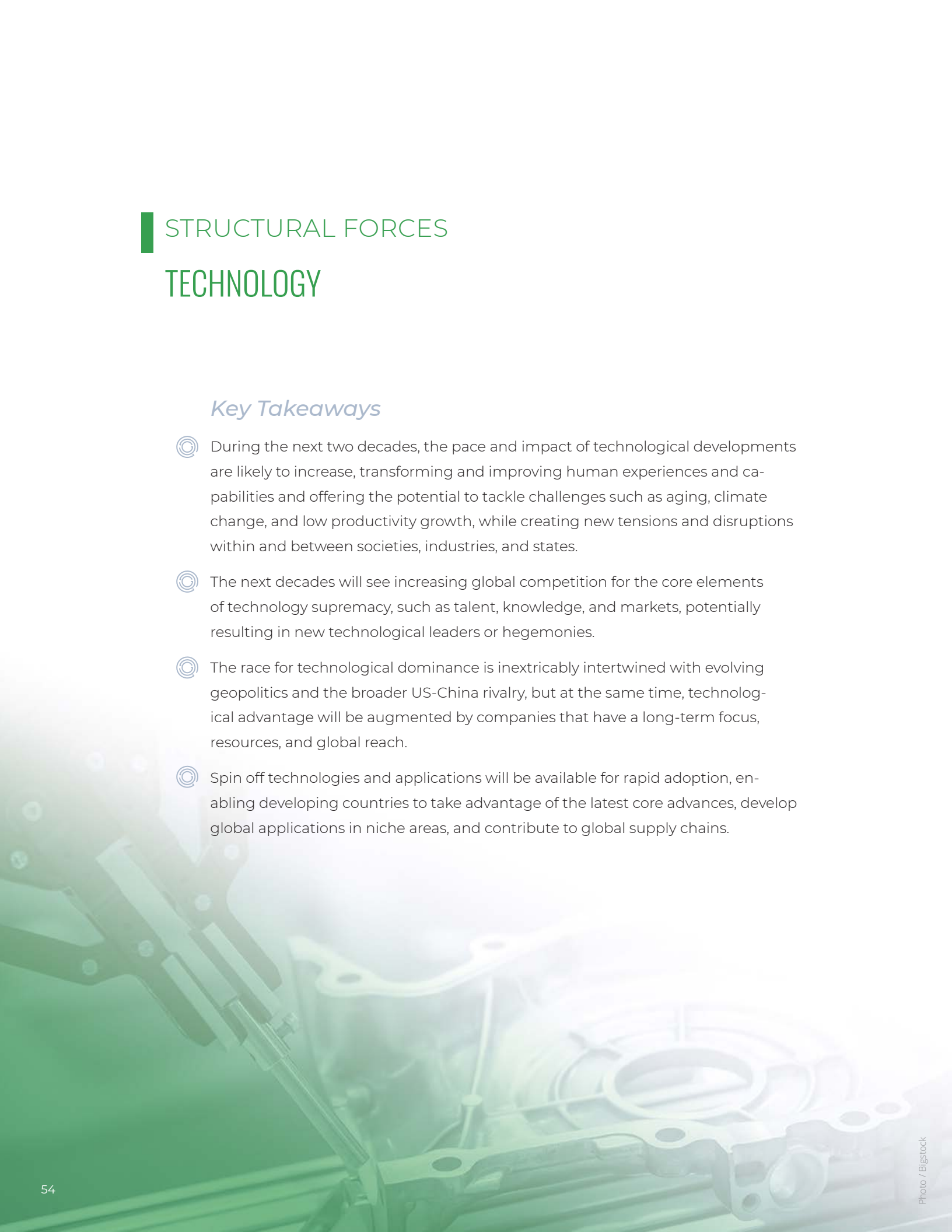
STRUCTURAL FORCES

TECHNOLOGY

Key Takeaways

- During the next two decades, the pace and impact of technological developments are likely to increase, transforming and improving human experiences and capabilities and offering the potential to tackle challenges such as aging, climate change, and low productivity growth, while creating new tensions and disruptions within and between societies, industries, and states.
- The next decades will see increasing global competition for the core elements of technology supremacy, such as talent, knowledge, and markets, potentially resulting in new technological leaders or hegemonies.
- The race for technological dominance is inextricably intertwined with evolving geopolitics and the broader US-China rivalry, but at the same time, technological advantage will be augmented by companies that have a long-term focus, resources, and global reach.
- Spin off technologies and applications will be available for rapid adoption, enabling developing countries to take advantage of the latest core advances, develop global applications in niche areas, and contribute to global supply chains.



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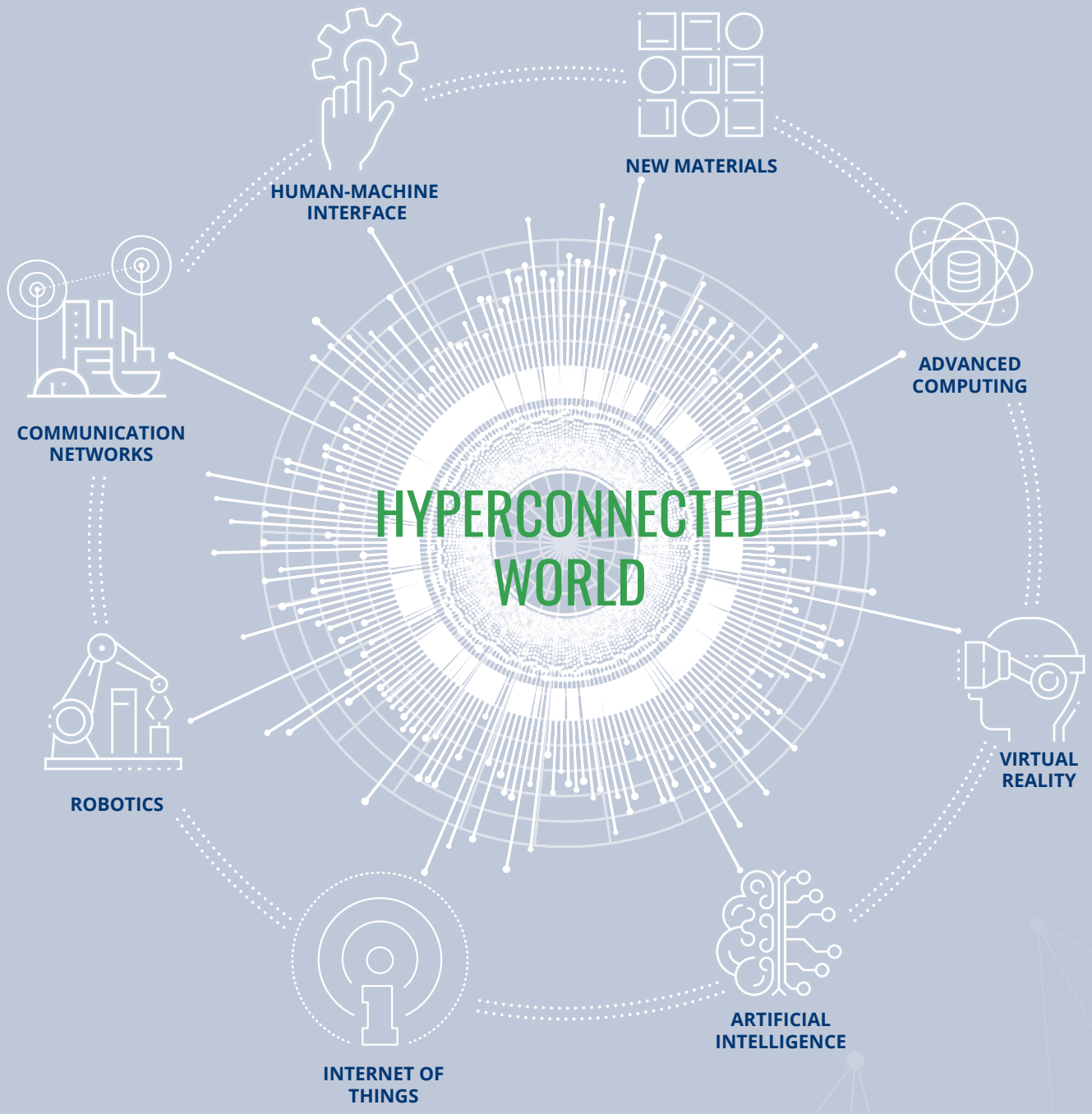
HUMAN-MACHINE INTERFACE
NEW MATERIALS
COMMUNICATION NETWORKS
ADVANCED COMPUTING
HYPERCONNECTED WORLD
ROBOTICS
VIRTUAL REALITY
INTERNET OF THINGS
ARTIFICIAL INTELLIGENCE

The increasing convergence of seemingly unrelated fields and the rise of global competition to generate and lock in advantage are accelerating the emergence of cutting-edge technologies.

Assessing technological trends and their broader implications is challenging because timelines remain uncertain, the path from foundational science to a transformational application can be difficult to discern, and the connections between a technology and its potential broader implications can be indirect and complex. Emerging technologies also raise myriad ethical, societal, and security questions—ranging, for example, from who we are as humans, to our impact on the environment, to the bounds of acceptable warfare.

TRENDS ACROSS EMERGING TECHNOLOGIES

Multiple trends are shaping the technology landscape of the next two decades, and while new technologies will not emerge uniformly or predictably, they are likely to share some common drivers and dynamics. The increasing convergence of seemingly unrelated fields and the rise of global competition to generate and lock-in advantage are accelerating the emergence of cutting-edge technologies. The diffusion of technological knowledge, the aggressive setting of standards to favor one technology solution over another, and ever shorter product development timelines will incentivize long-term strategy and rapid decisionmaking to avoid missteps and falling behind competitors.

Scientific Convergence Sparking Innovation. The convergence of seemingly unrelated areas of scientific research and technological applications is making the rapid development of novel applications possible, practical, and useful. For example, the smartphone was enabled by decades of basic research and development in electronics, antennas, materials, batteries, telecommunications networks, and user interfaces. By 2040, the increasing convergence of technologies, such as artificial intelligence (AI), high-speed telecommunications, and biotechnology, will be augmented by increased understanding of the social and behavioral sciences to enable rapid breakthroughs and user customized applications that are far more than the sum of their parts. Taken together, these technology platforms can then provide a foundation for rapid innovation while lowering the barriers to market entrance.

Growing Competition for Dominance. The race for technological dominance is inextricably intertwined with evolving geopolitics and is increasingly shaped by broader political, economic, and societal rivalries, particularly those associated with China's rise. Amassing the resources to sustain broad technology leadership, including the concentration of human talent, foundational knowledge, and supply chains, requires decades of long-term investment and visionary leadership. Those focusing their resources today are likely to be the technology leaders of 2040. In open economies, a mix of private efforts and partnerships between governments, private corporations, and research programs will compete with state-led economies, which may have an advantage in directing and concentrating

resources, including data access, but may lack the benefits of more open, creative, and competitive environments.

Technologies Diffusing Globally. Spin off technologies and applications are often available for rapid adoption in nearly every region of the world, enabling even developing countries to take advantage of the latest core advances, develop global applications in niche areas, or contribute to the supply chains of more advanced economies. Many states will seek to accelerate and harness this process, sponsoring focused efforts, such as regional alternatives to Silicon Valley or biotechnology incubators that will increase the risk of surprise from novel applications arising from unexpected locations.

Timelines Shrinking. The time to develop, deploy, mature, and then retire technologies is moving from decades to years and sometimes faster. Multiple actors, including corporations and states, at the forefront of emerging technology may deploy and exploit a new technology before others get off the starting blocks. Those trying to catch up, especially in developing countries, may be increasingly forced to choose technologies before the implications of those choices are fully understood, risking investment in technological dead ends or falling hopelessly behind. Planned economies may be able to react faster to emerging technology developments, potentially at the cost of reduced technological diversity and efficiency.

TECHNOLOGIES DRIVING TRANSFORMATION

Although technology advances in unpredictable ways, shaped by unexpected difficulties and unanticipated breakthroughs, some technological areas appear to offer the po-

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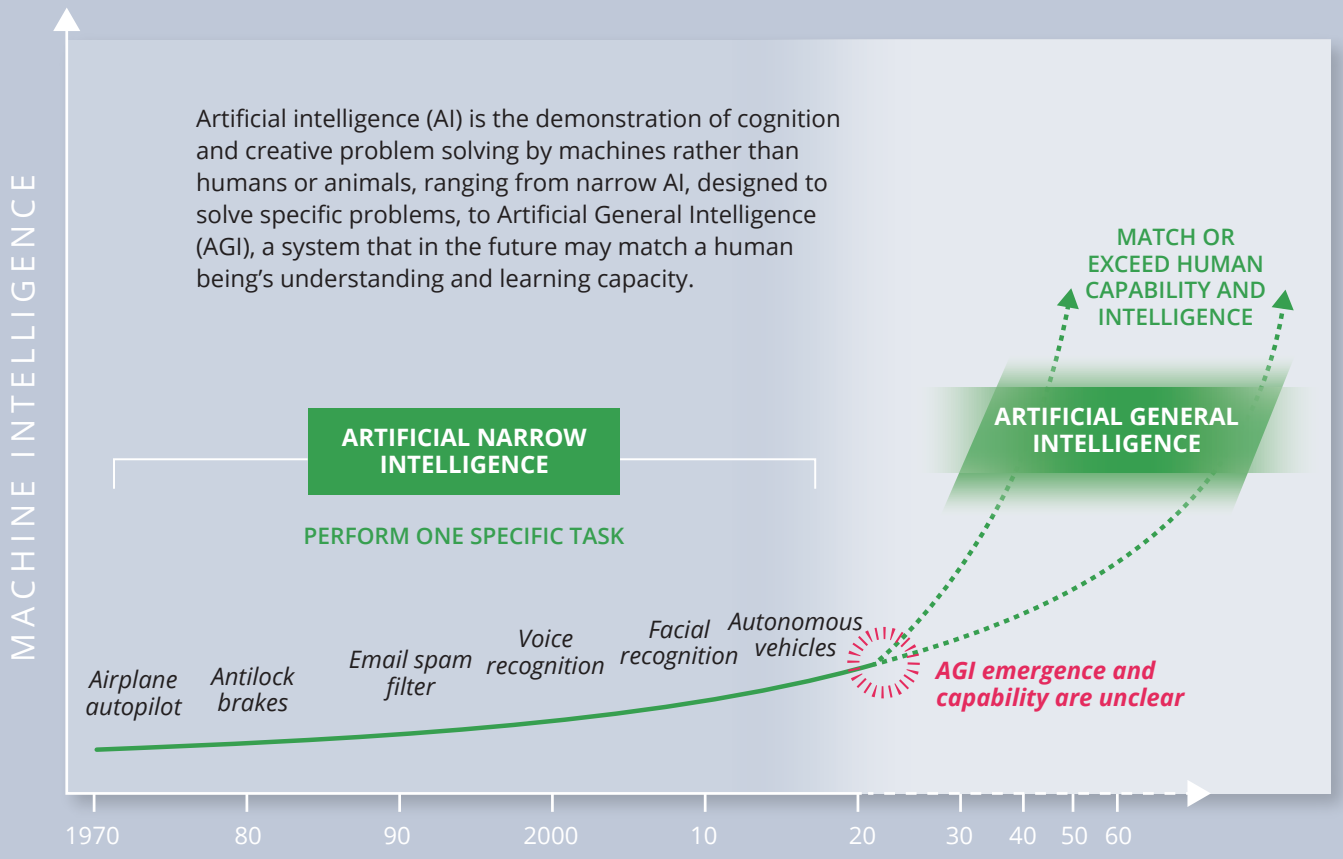
TRAJECTORY OF ARTIFICIAL INTELLIGENCE



tential for transformative change and provide examples of the potential consequences of new technologies in the coming decades. The following sections on AI, biotechnology, and materials and manufacturing—selected after consultation with technology leaders—highlight the potential benefits and risks of new technologies individually and collectively in creating a future hyperconnected world. Advances in these areas will combine with other technologies, such as energy storage, to shape societies, economies, and perhaps the nature of power.

Artificial Intelligence Becoming Mainstream

AI is the demonstration of cognition and creative problem solving by machines rather than humans or animals, ranging from narrow AI, designed to solve specific problems, to Artificial General Intelligence, a system that in the future may match or exceed a human being's understanding and learning capacity. By 2040, AI applications, in combination with other technologies, will benefit almost every aspect of life, including improved healthcare, safer and more efficient transportation, personalized education, improved software for everyday tasks, and increased agricultural crop yields. Political and business leaders worldwide are seeking global talent and are pouring resources into developing AI, hoping to be among the first to use it to reshape societies, economies, and even war. Enabled by concurrent increases in high-quality data, computing capability, and high-speed communication links, AI will challenge leaders to keep pace

and reap the benefits while mitigating harmful effects, such as threats to privacy and liberty.

Although many new AI developments will be available globally, there are disproportionate advantages for nations that can afford to support, develop, and adopt AI now. Widespread adoption of AI, particularly in warfare, also increases the risk of intentional misuse or unintended engagement or escalation.

Industry and Labor Transformed. AI will transform almost all industries and disrupt the global labor force, creating new job fields, eliminating others, and driving significant economic and social redistributions. Human-machine teaming will be common for many future jobs. To harness the advantages of AI while mitigating unemployment, countries and corporations will need to focus on education and retraining their workforce.

Data Will Be King. AI dependent industries and organizations of the future will require massive quantities of data to operate efficiently and competitively. Institutions, companies, and countries already investing in ways to acquire, classify, store, and monetize data will have advantages. The unprecedented amounts of data available in 2040 will provide valuable insights and capabilities but also open up access, privacy, ownership, and control of data as areas of increasing competition and conflict.

Security and Privacy Reimagined. Current notions of privacy will continue to evolve, with individuals needing to share more personal information for access to applications, and tracking becoming ubiquitous. Authoritarian governments are likely to exploit increased data to monitor and even control their populations. Moreover, many companies and organizations will also have powerful tools such as video manipulation, or deep fakes, to improve tailored marketing or advance a particular narrative. Emerging AI applications may also become potential targets for data manipulation to skew their output.

Ethics of Autonomy. AI's development and the level of human involvement in decision-making, if any, will continue to raise ethical concerns, and perspectives on ethical obligations are likely to be differ globally. In addition, the opaque nature of AI decisionmaking increases the possibility of unintentional bias, discrimination, unexpected outcomes, or intentional misdirection. Cooperation to advance trustworthy AI, with transparent and clear decisionmaking processes, may improve trust and confidence for all parties. Although many countries will develop strict rules on the use of personal data, there will be debate on whether these rules can coexist with the full realization of AI capabilities.

AI Enhanced Warfare. AI will confer strong advantages to countries that incorporate AI into their military systems. AI will enhance the performance of existing weapons, defenses, and security systems, both physical and cyber, while counter-AI techniques, designed to negate or confuse AI decision making, also are likely to emerge.

Smart Materials and Manufacturing Are Building a New World

By 2040, advances in novel materials, coupled with smart manufacturing, will reshape the production of everything from consumer goods to high-end military systems, reducing costs, extending capabilities, shifting supply chains, and enabling entirely new design options. The period of rapid change we are entering is often referred to as a Fourth

Industrial Revolution because of its potential to improve standards of living while possibly disrupting traditional industries, jobs, supply chains, and business models.

Materials and manufacturing are inextricably linked in a long-standing virtuous cycle, where advances in one drive advances in the other. Although this cycle alone could continue to drive progress for decades to come, it most likely will be accelerated by convergent advances in high performance computing, materials modeling, AI, and bio-materials. Increased connectivity will complement this growth by allowing advances to be distributed and accessible across the globe.

Increased Design Options. Additive manufacturing (AM), more commonly known as 3D printing, is being used to fabricate an increasing variety of materials, from titanium to explosives, in smaller facilities and with less expertise, bringing advanced manufacturing capabilities to small companies and individuals worldwide. Despite some technical hurdles and questions of reliability, AM is driving a revolution in modern manufacturing by enabling rapid prototyping, highly customized parts, on-site production, and the fabrication of shapes that would otherwise be impossible.

Adapting On The Fly. Advances in information systems, including computational modeling and machine learning, combined with advanced physical systems, such as a robust industrial Internet of Things and advanced robotics, are likely to enable fully integrated, collaborative manufacturing systems that respond in real time to meet changing conditions in the factory, in the supply network, and in demand.

Design What You Need. Materials today are undergoing a revolutionary transformation, shifting from off-the-shelf materials to optimized materials and processes designed for custom products. Combined with additive manufacturing, materials-by-design will enable great strides in making everything from airplanes to cell phones stronger, lighter, and more durable.

Assemble What You Need. The coming decades will see advances in the development of new materials with previously unobtainable properties, enabling previously unreachable levels of performance for many applications. Two-dimensional materials, metamaterials, and programmable matter will have unusual strength, flexibility, conductivity, or other properties that enable new applications.

Biotechnology Enabling Rapid Innovation

Improved capability to predictably manipulate biological systems, augmented by advances in automation, information, and materials sciences, is spurring unprecedented innovation in health, agriculture, manufacturing, and cognitive sciences. By 2040, biotechnology innovations most likely will enable societies to reduce disease, hunger, and petrochemical dependence and will transform how we interact with the environment and each other. Societies will be challenged to harness these beneficial advancements while addressing the market, regulatory, safety, and ethical concerns surrounding these technologies—for example, genetically modified crops and foods.

Biotechnology is likely to make significant contributions to economic growth during the next two decades, potentially affecting 20 percent of global economic activity by 2040, notably in agriculture and manufacturing, based on

BENEFITS AND RISKS OF ADVANCED BIOTECHNOLOGY APPLICATIONS

BENEFITS	APPLICATION	RISKS
Misdiagnoses plummet and healthcare outcomes improve.	**DIGITAL HEALTH / PERSONALIZED MEDICINE** *Tailored medical treatments using AI to combine data from genetic sequencing, diagnostics, and biomonitoring.*	*Access disparities due to costs or location. Personal health data misuse or manipulation.*
Rapid, more effective medical treatments.	**ON DEMAND MEDICINE PRODUCTION** *Cell-and gene-based therapies, combined with improvements in drug design and production, for faster disease response.*	*Disputes over R&D prioritization in developed vs. developing countries.*
Reduce delays and rejections of organ transplants and repairs.	**BIOPRINTING AND XENOTRANSPLANTATION** *Additive manufacturing to "print" biological parts for medical testing or tissue replacement, grow human-compatible organs in animals for transplantation.*	*Access disparities due to the high up-front costs.*
Major reduction in inherited genetic diseases.	**REPRODUCTIVE ENGINEERING** *Using genomic technologies to select and modify human embryos for broad range of traits and abilities.*	*Ethical and social divides over applications. Unequal access.*
Novel treatments for neurological disorders. Enhanced cognition and expanded perception.	**COMPUTER-HUMAN INTERFACES** *Machine augmentation of human cognitive processes.*	*Tensions between augmented and non-augmented individuals. New cyber/bio vulnerabilities.*
Improved speed and reliability in designing and making novel materials, medicines.	**BIO-MANUFACTURING** *Bio-design and production of enhanced or highly specified materials, medicines and foods.*	*Increased potential for misuse and workforce restructuring.*
Ready production of new and novel molecules, materials and treatments.	**SYNTHETIC ORGANISMS** *Genetically modified organisms and biological processes create new materials and medicines.*	*Potential for weapons applications or accidental misuse. Unknown environmental impacts.*
Make barren or depleted lands productive. Mitigate human-induced and natural threats to the environment.	**ENVIRONMENTAL RESTORATION** *Large-scale ecological intervention, through biotechnology, reforestation, or ocean engineering creates, manipulates, or rescues damaged environments.*	*Unintended, potentially global environmental or public health consequences.*
Practically unlimited capacity for long-term data storage.	**DNA-BASED DATA STORAGE** *DNA used to encode and store data.*	*Increased potential for long-term social monitoring.*
Increased variety of cheaper, more nutritious foods created with lower environmental impact.	**TRANSFORMED AGRICULTURE AND FOOD PRODUCTION** *Automated precision production processes and integrated crop-livestock systems use genetically altered organisms.*	*Reduced biodiversity, social tensions over genetic modification, workforce and supply chain disruptions.*

NEW TECHNOLOGIES FUELING SPACE COMMERCE AND SPARKING COMPETITION

The space landscape in 2040 will combine emerging technology with a maturation of today's capabilities to help drive commercialization and introduce new applications. Services, such as communications, navigation, and satellite imagery, will become ubiquitous offering improved capabilities, lower costs, and increasing efficiencies. The efforts of both government and commercial actors will establish new domains of space competition, particularly between the United States and China.

Space Exploration Expands

By 2040, an increasing number of countries will be participating in space exploration as part of international cooperative efforts. By doing so, these countries will acquire national prestige, opportunities for scientific and technical advancement, and potential economic benefits. Although governments will remain the primary source of funding to support large-scale space exploration activities, the role of commercial entities will expand dramatically in most aspects of space activities. Commercial efforts will coexist, and probably cooperate, with government-funded space programs, advancing space technologies.

China As A Space Power

By 2040, China will be the most significant rival to the United States in space, competing on commercial, civil, and military fronts. China will continue to pursue a path of space technology development independent of that involving the United States and Europe and will have its own set of foreign partners participating in Chinese-led space activities. Chinese space services, such as the Beidou satellite navigation system, will be in use around the world as an alternative to Western options.

Space Supporting Government and Military Needs

Enhanced space services and new technology will be available for military applications as well as civil government and commercial use. National space assets will be particularly coveted as governments remain concerned about the possibility that commercial or foreign government space services could be denied in conflict.

On-Orbit Activities Become Routine

By 2040, governments probably will conduct routine on-orbit servicing, assembly, and manufacturing activities, enabled by advanced autonomy and additive manufacturing, to support national space systems and international efforts. Commercial companies probably will offer on-orbit services, such as repair, remote survey, relocation, refueling, and debris removal. On-orbit services will be used to upgrade satellites, extend their functional lives, and allow for new types of space structures, such as extremely large or complex instruments, but they may need government support to establish the industry.

AI Goes to Space

AI will allow innovative use of space services by assisting with operation of large satellite constellations and space situational awareness capabilities. AI will also support the fusion and analysis of enormous volumes of high-quality, continuously collected data, driven partly by hyperconnected space and ground systems.

bioeconomy growth rates relative to gross domestic product (GDP). In 2019, the United States estimated its bioeconomy at nearly $1 trillion dollars annually, or approximately 5.1 percent of its total economy, while European Union and UN estimates from 2017-19, which apply a broader definition of bioeconomic activities, show biotech contributing as much as 10 percent to Europe's economy.

Hyperconnectivity Uniting and Separating Societies

By 2040, the world will have orders-of-magnitude more devices, data, and interactions, linking together all aspects of modern life and crossing political and societal boundaries. Increasing speed and global access will provide nations, corporations, and even individuals with services and resources once limited to prosperous countries. This hyperconnected world is a future already beginning to emerge; next generation networks, persistent sensors, and myriad technologies will fuse together in a global system with billions of connected devices. Today's ubiquitous public cameras, for example, will lead to tomorrow's smart cities, where optical and other sensors combine with AI to monitor people, vehicles, and infrastructure globally.

By some estimates, the current Internet of Things, a precursor to a hyperconnected future, will reach 64 billion objects by 2025, up from 10 billion in 2018—all monitored in real time. Looking forward, a hyperconnected world could support up to 1 million devices per square kilometer with next generation cell phone systems (5G), compared with the 60,000 devices currently possible with current cell networks, with even faster networks on the horizon. Networked sensors will become ubiquitous; more than 20 billion devices were operative in 2020, and with new terrestrial networks combined with an increase in space-based services, it is projected that hundreds of billions and eventually trillions of devices may be connected globally.

Accelerated Societal Change. Privacy and anonymity may effectively disappear by choice or government mandate, as all aspects of personal and professional lives are tracked by global networks. Real-time, manufactured or synthetic media could further distort truth and reality, destabilizing societies at a scale and speed that dwarfs current disinformation challenges. Many types of crimes, particularly those that can be monitored and attributed with digital surveillance, will become less common while new crimes, and potentially new forms of discrimination, could arise.

New Cybersecurity Paradigms. Greater connectivity almost certainly will increase the vulnerability of connected individuals, institutions and governments as the presence of hundreds of billions of connected devices vastly increases the cyber-physical attack surface. In addition, cyber security enforcement based on geographic borders is likely to become less relevant in an increasingly global web.

BROADER IMPLICATIONS OF TECHNOLOGY EVOLUTION

Emerging technologies are rapidly improving a broad range of human experiences and capabilities, but at least in the short term, these same technologies may disrupt longstanding systems and societal dynamics, forcing individuals, communities, and governments to adjust and find new ways of living, working, and managing. As with any disruption, some will thrive whereas others will struggle, potentially facing increasing inequalities and imbalances. Emerging technologies are not solely responsible for the following developments, but they are likely to aggravate and amplify them.

NASA / Unsplash

Solving Problems Fast. As the global COVID-19 vaccine development effort has showcased, technologies—often integrated in new and imaginative ways—can be quickly reapplied from their original use to solve crisis needs. The research that enabled the unprecedented and rapid development of effective COVID-19 vaccines built on decades of foundational investments in the health sciences. Similarly, challenges decades in the making, such as climate change, may be moderated by bringing together suites of technological solutions that each address one element of a much larger issue.

Technology as Geopolitical Power. Technology is a tool of national power that the United States has long led through investments in research, innovation, and development. The next decades will see increasing global competition for the core elements of technology supremacy, such as talent, knowledge, and markets, potentially resulting in new technological leaders or hegemonies in the 2030s. Complex international supply chains, the global diffusion of innovation, and investments by geopolitical rivals could further impede the unilateral use of technology by nations to achieve their goals. Conditions are ripe for both greater international cooperation as well as new types of multifaceted competition and conflict that could define the coming era.

Aggravating Social Tensions. The pace of technological change could increase societal tensions between those with the access, ability, and will to adapt and those who are unable or unwilling to change. With the rapid spread and adoption of technologies, some individuals, communities, and countries could make rapid advancements while others may be left behind with little hope of catching up, exacerbating inequalities within and between states.

Technological adoption also may outpace ethical maturity and regulation, creating persistent and potentially corrosive social anxiety and political divisions. These tensions could be further inflamed by the use of manufactured or AI targeted messaging such as deep fakes.

Complicating Government-Corporate Relationships. Public-private partnerships for investment, research, and development have been critical for attaining many technological breakthroughs and advantages, but core corporate and national interests do not naturally align. Large technology companies increasingly have resources, reach, and influence that rivals and even surpasses some states. National interests in maintaining technological control and advantage as well as protecting national security can be at odds with corporate interests in expanding global market share and increasing profits.

Disrupting Industries and Jobs. The pace of technological change, notably developments in advanced manufacturing, AI, and biotechnology, may hasten disruptions to manufacturing and global supply chains, eliminating some modes of production and jobs and bringing supply chains closer to markets. Shifting supply chains could disproportionately affect less advanced economies, while many new jobs will require workers with improved or retooled skills.

Enabling Governance, Threatening Freedom and Privacy. The technology-saturated and hyperconnected future will offer leaders and governments new tools to monitor their populations, enabling better service provision and security but also offering greater means of control. The same technologies that empower citizens to communicate, organize, and monitor their health are providing increasing amounts of data to governments and the private sector. Governments, especially authoritarian governments, will exercise unprecedented surveillance capabilities to enforce laws and provide security while tracking and de-anonymizing citizens and potentially targeting individuals.

Stimulating Debates Over Openness. The prospects of a hyperconnected world will stimulate debates and divisions within and between states about the benefits and risks of open, connected networks. As global networks become increasingly interconnected, it may be more difficult to maintain a segregated or closed system, and efforts to block the broader Internet potentially could irreparably cut off closed systems from the global economy.

Existential Risks. Technological advances may increase the number of existential threats; threats that could damage life on a global scale challenge our ability to imagine and comprehend their potential scope and scale, and they require the development of resilient strategies to survive. Technology plays a role in both generating these existential risks and in mitigating them. Anthropomorphic risks include runaway AI, engineered pandemics, nanotechnology weapons, or nuclear war. Such low-probability, high-impact events are difficult to forecast and expensive to prepare for but identifying potential risks and developing mitigation strategies in advance can provide some resilience to exogenous shocks.