Office of the Deputy Assistant Secretary
of the Army (Research & Technology)

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Emerging Science and Technology Trends: 2017-2047

A Synthesis of Leading Forecasts

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EXECUTIVE SUMMARY

This is the fourth annual report on emerging trends in science and technology (S&T) published by the Deputy Assistant Secretary of the Army for Research and Technology (DASA R&T). As in prior years, the report has two primary objectives. First, it is intended to inform leaders across the U.S. Army and stakeholders in the joint, interagency, and international community about S&T trends that are likely to influence the future operating environment and shape warfighting capabilities over the next 30 years. Second, it is intended to spark strategic dialogue around the kind of S&T investments the Army should make to ensure that our Soldiers maintain overmatch across the range of likely future operating environments.

This 2017 version of the S&T Strategic Trends report synthesizes 52 S&T forecasts that have been published over the past five years by government agencies in the U.S. and abroad, industry leaders, international institutions, and think tanks. An initial review of the source documents isolated 947 individual trends related to science and technology, as well as trends related to broader contextual factors that will shape the evolution of S&T over the coming decades. This data set was further analyzed using natural language processing (NLP) techniques, which yielded a set of 10 cross-cutting science and technology trends:

- Robotics, artificial intelligence (AI), and automation
- Advanced materials and manufacturing
- Energy production, harvesting, storage, and distribution
- Biomedical science and human augmentation
- Quantum computing
- Mixed reality and digital mimicry
- Food and water security technologies
- Synthetic biology
- Space technologies
- Climate change adaptation technologies

This year's report expands the analytics presented in prior editions by including the results of an inaugural survey of Army subject matter experts' (SMEs') perspectives on the 10 emerging S&T trends. A total of 869 scientists, engineers, program managers, and senior leaders from across the Army S&T enterprise completed a digital survey that asked them to gauge the relative level of risk and opportunity each trend is likely to present for the Army over the next 30 years. In addition, the SMEs were asked to assess the likelihood that the United States will sustain technological dominance in these emerging S&T domains. The results present a richer picture of how these trends are likely to impact the Army. Risk and opportunity were highly correlated, possibly reflecting the emerging threat of near-peer competitors who will be increasingly capable of exploiting advanced technology. Furthermore, while the SMEs anticipated that the U.S. would maintain a slight edge in most technology domains, dominance was not assured.

In addition to examining S&T trends, this report discusses six "contextual trends" that represent broad forces that are likely to shape the evolution of science and technology over the next 30 years. The contextual trends discussed in this report are: urbanization, climate change, resource constraints, shifting demographics, the globalization of innovation, and the rise of a global middle class. The major takeaway from these contextual factors is that the United States is unlikely to maintain its historic dominance in innovation. Instead, the locus of innovation is likely to shift and diffuse, as countries like China and India begin ramping up their own S&T agendas. China, in particular, is beginning to demonstrate an ability to innovate in its own right.

As with previous editions of the S&T Strategic Trends report, a set of "trend cards" are included at the end of the report. These cards provide additional detail on the S&T trends, including a synopsis of each trend, along with summaries of enabling S&T domains, recent developments that signal how each trend might evolve, and a high-level consideration of the impacts each trend might have on society, politics, economics, the environment, and defense. These trend cards provide a convenient reference for strategic conversations about how the Army can best capitalize on emerging capabilities to sustain dominance in the future operating environment.

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BACKGROUND

This is the fourth annual report on emerging trends in science and technology (S&T) published by the Deputy Assistant Secretary of the Army for Research and Technology (DASA R&T). As in prior years, the report has two primary objectives. First, it is intended to inform leaders across the U.S. Army and stakeholders in the joint, interagency, and international community about S&T trends that are likely to influence the future operating environment and shape warfighting capabilities over the next 30 years. Second, it is intended to spark strategic dialogue around the kind of S&T investments the Army should make to ensure that our Soldiers maintain overmatch across the range of likely future operating environments. This report is part of the DASA R&T's broader Technology Wargaming program, which seeks to provide strategic foresight research and analysis in support of both S&T investment planning and Unified Quest, the Army's annual future study program sponsored by the Chief of Staff and conducted by the Army Capabilities Integration Center (ARCIC).

Technology has been central to the American way of war throughout the nation's history,[1] and it is safe to assume that scientific and technological advancements will remain an important foundation for U.S. Army capabilities in the future. There are robust, ongoing discussions across the Army and the broader national security enterprise on the potential risks and opportunities of several emerging technological domains, such as robotics and autonomous systems.[2,3] The implications of other domains, such as synthetic biology, are still unclear.

Technological change is taking place against the backdrop of the most profound realignment of the global economic and political landscape since the fall of the Soviet Union. The United States military has long relied on an overwhelming advantage in research, development, and innovation that is unlikely to persist much longer. As China, Russia, and other nations modernize their militaries through investments in science and technology, it will become essential for the U.S. Army to make the most effective use of S&T investments to stay ahead of emerging threats.

Effective investment strategies start with an understanding of emerging trends. Therefore, the aim of this edition of the S&T Strategic Trends report is to identify the major developments in science and technology that are likely to influence Army capabilities through the year 2047. The definition of "influence" adopted in this report is intentionally broad, and includes potential implications of emerging technologies for enhancing U.S. land warfare capabilities, the capabilities of potential adversaries, and the broader socio-cultural and geopolitical landscapes that will frame future conflicts.

Every year, governments, industry leaders, think tanks, nonprofits, and other organizations publish dozens of analyses of science and technology trends through rigorously-developed, open source reports. Many of these institutions, such as the U.S. National Intelligence Council, the UK Ministry of Defense, and the McKinsey Global Initiative, share the Army's imperative to closely examine the influence of S&T on social, political, economic, environmental, and defense-related issues. Therefore, the trend analyses published by these organizations provide the Army with a rich set of data for mining trends that have significant potential for impacting the future force. Rather than "reinventing the wheel" the approach adopted in this report is to synthesize the collective insights of the professional foresight community to identify trends that are highly likely impact the U.S. Army over the coming decades.

In that vein, a comprehensive literature search was conducted to identify trend forecasts published by foreign and domestic government agencies, industry analysts, academic organizations, and think tanks. A total of 52 reports were selected based on the following criteria:

- All of the reports had to be the product of rigorous and well-documented research conducted by reputable organizations with a track record of producing high-quality trend analysis.

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[1] Mahnken, T.G. (2010). Technology and the American Way of War Since 1945. NY: Columbia University Press.

[2] TRADOC Mad Scientist Initiative (May 2017). Robotics, Artificial Intelligence, and Autonomy: Visioning Multi-Domain Warfare in 2030-2050. Technical Report.

[3] DASA R&T (May 2017). Artificial Intelligence and Robotics Ideation Exercise. Final Report.

- All of the reports had to have been published within the past 5 years.
- All of the reports had to address science and technology trends that could influence Army operations and the future operating environment over the next 30 years.
- All of the reports had to address a wide range of science and technology trends. Narrow forecasts related to highly specific industries or technology domains were not included in this analysis.

Appendix A provides a complete bibliography of the sources that were used to conduct this synthesis of emerging science and technology trends. Of the 52 sources included in this year's synthesis, 32 were carried over from the 2016 Emerging Trends report, with 21 new sources added for this edition. A content analysis of these documents (described in Appendix B) identified 947 specific trends related to science and technology and major social, economic, environmental, and political trends that are likely to shape the context in which scientific and technological developments will occur.

Further analysis of the trend data using natural language processing techniques revealed 10 common science and technology "mega-trends" that have the potential to shape future Army operations and the future operating environment. The analysis also identified seven cross-cutting contextual trends that will influence how science and technology could evolve. Details on the analysis methodology are presented in Appendix B.

This year's report expands the analytics presented in prior editions by including the results of an inaugural survey of Army subject matter experts' (SMEs') perspectives on the 10 emerging S&T trends. A total of 869 scientists, engineers, program managers, and senior leaders from across the Army S&T enterprise completed a digital survey that asked them to gauge the relative level of risk and opportunity each trend is likely to present for the Army over the next 30 years. In this context, opportunity and risk were defined as the emergence of new technology-enabled capabilities that could provide a tactical edge to the U.S. and/or potential adversaries within the next 30 years, affecting the Army's relative strength. In addition, the SMEs were asked to assess the likelihood that the United States will sustain technological dominance in these emerging S&T domains. The results, which are presented below, present a richer picture of how these trends are likely to impact the Army. Complete details on the survey methodology are given in Appendix B.

The remainder of this report is divided into two parts. Part 1 reviews the science and technology trends that were identified through the synthesis of open source forecasts. As with the 2016 Trends report, a set of "trend cards" is provided at the end of the report. These cards provide a convenient synopsis of key information for each trend, including enablers for scientific and technical progress, recent developments that signal how each trend might evolve over the coming decades, and a brief review of the impacts that each trend might have on society, politics, the economy, the environment, and national defense. Part 1 of the report also discusses insights from the SME survey on risk, opportunity, and technological dominance. Part 2 of the report reviews the seven contextual trends that emerged from analysis of the source documents. While the focus of this report is on science and technology horizon scanning, consideration of these contextual trends speaks to the broader undercurrents that are likely to shape the critical nexus of S&T, sociopolitical change, and national security over the coming decades.

PART 1: EMERGING S&T TRENDS

As discussed above, this edition of the S&T Emerging Trends report incorporate 52 horizon scans conducted within the past five years by government agencies, industry groups, and think tanks. Mining these documents for trends produced a corpus of 947 trends related to the emerging science and technology landscape. Statistical topic modeling identified 10 core trends that are likely to influence the U.S. Army over the next 30 years:

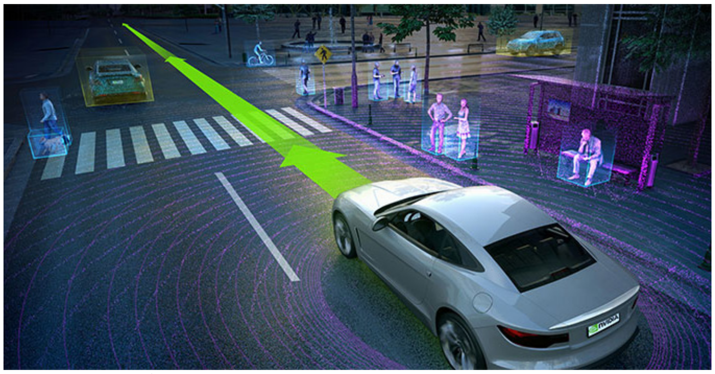
- Robotics, autonomous systems, and automation
- Advanced materials and manufacturing
- Energy production, harvesting, storage, and distribution
- Biomedical science and human augmentation
- Quantum computing
- Mixed reality and digital mimicry (e.g., AR, VR, voice synthesis)
- Food and water security technologies (e.g., water harvesting, lab-grown meat)
- Synthetic biology
- Space technologies (e.g., asteroid mining, commercial space travel, antisatellite weapons)
- Climate change adaptation technologies (e.g., geoengineering, super-carbon-absorbing plants)

This section of the Report presents these trends, using data from the source documents and other, topic-specific analyses to illustrate potential development vectors for each trend and how each trend could impact the Army. Following the description of each trend, the report presents data from the SME survey on the relative degree of risk and opportunity each trend is likely to present, as well as the likelihood of sustained U.S. technological dominance in these 10 S&T domains.

Robotics, AI, and Automation

Robotics, artificial intelligence (AI), and autonomation are already deeply integrated into global economic and defense structures. These technologies can be found in almost every market sector, including agriculture, finance, customer support, and logistics. For example, the U.S. credit and banking industries use intelligent software agents to monitor over 1.3 billion credit cards for fraud, flagging potential cases within 10 milliseconds.[4] AI is beginning to take on tasks previously thought to be reserved for highly trained experts. IBM's Watson for Oncology was "trained" to diagnose cancer and recommend courses of treatment by ingesting 12 million pages of unstructured text from over 200 medical textbooks and 290 journals. A recent study found that Watson's treatment recommendations matched those made a panel of human oncologists in approximately 90% of routine cases.[5] Defense applications of robotics and AI are also growing – the U.S. spent $3 billion on procuring unmanned systems in 2016.[6]

All signs point to continued acceleration in the adoption of robotics and AI. A 2016 study by the Boston Consulting Group found that the global market for autonomous vehicles is likely to grow from $42 billion in 2025 to over $77 billion by 2035.[7] The total economic impact of autonomous vehicles could top $7 trillion per year by 2050.[8] Impacts in finance,



Source: www.nvidia.com

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[4] Defense Science Board (June 2016). DSB summer study on autonomy. Available from http://www.acq.osd.mil/dsb/reports/2010s/DSBSS15.pdf.
[5] http://www.healthcareitnews.com/news/ibm-watson-accurately-matches-oncologists-advice-study-finds
[6] DSB Summer Study on Autonomy
[7] https://www.bcg.com/en-us/expertise/industries/automotive/autonomous-vehicle-adoption-study.aspx
[8] https://newsroom.intel.com/newsroom/wp-content/uploads/sites/11/2017/05/passenger-economy.pdf?cid=em-elq-26916&utm_source=elq&utm_medium=email&utm_campaign=26916&elq_cid=1494219

health care, and the service industry will likely meet or exceed that level of growth.

The Defense Science Board 2016 Summer Study on Autonomous Systems identified many potential applications of robotics and AI to U.S. national security. The Army would likely benefit from many of these capabilities, including:

- Automated cyber response
- Organic tactical unmanned aircraft (UA) to support ground forces
- Predictive logistics and adaptive planning
- Early warning system for understanding global social movements
- Autonomous swarms that exploit large quantities of low-cost assets
- Autonomous cyber resilience for military vehicle systems

Furthermore, it is likely that the Army will be able to leverage significant private sector investments in robotics and AI development as these technologies become foundational to the future economy. It is possible that the service may realize numerous efficiencies in research and development, as well as sustainment of fielded systems, by capitalizing on emerging standards for robotic system components, AI algorithms, and human-robot interaction techniques. Army-specific funding could support hardening of these systems against cyberattacks and enhancing durability and sustainment footprints of robotic systems.

In recent years, leading scientists and technologists such as Stephen Hawking and Elon Musk have voiced concern about the risk existential threat from “runaway AI.”[9] Fears of a robot uprising date back to the very origin of the word – the Czech writer Karel Capek’s 1920 play Rossumovi Univerzální Roboti (Rossum’s Universal Robots) introduced the term “robot” and envisioned human extinction at the hand of autonomous servants. While most experts do not believe we are in imminent danger from autonomous systems, it is worth noting that the rapidly growing complexity of modern AI is beginning to outstrip our ability to understand its inner workings. Deep learning – a technology that allows intelligent systems to learn how to solve complex problems independent from human intervention – will be a keystone of many emerging robotics applications. However, the algorithms that underlie an agent trained using deep learning are fundamentally a black box – even the developers do not understand how these systems work.[10] A lack of insight into the inner workings of the AI “brain”, coupled with their growing integration into all facets of society, could pose a significant threat. It is most likely that this threat will emerge as a result of unintended and unforeseen interactions among automated systems. For example, in 2010 a negative feedback loop spontaneously emerged in automated stock trading systems, causing a “flash crash” that led to $3 trillion in losses in just 36 minutes.[11] More recently, Facebook shut down a research project on negotiation between AI agents after the chat bots spontaneously developed their own language[12]. Experts stressed that the “language” these bots used was highly specific to the task they were being trained to conduct, and that news reports playing on public fears of “spontaneously sentient” AI were overblown. However, this case highlights the growing disconnect between AI capabilities and public policies, regulations, and social norms.


Source: www.deepinstinct.com

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[9] http://www.npr.org/2017/07/17/537686649/elon-musk-warns-governors-artificial-intelligence-poses-existential-risk

[10] https://www.technologyreview.com/s/604087/the-dark-secret-at-the-heart-of-ai/

[11] Vuorenmaa, T. A. and Wang, L. (2014). An agent-based model of the Flash Crash of May 6, 2010, with policy implications. Available at http://dx.doi.org/10.2139/ssrn.2336772.

[12] https://www.cnbc.com/2017/08/02/facebook-bot-controversy-highlights-peoples-fears-about-ai-and-robots.html

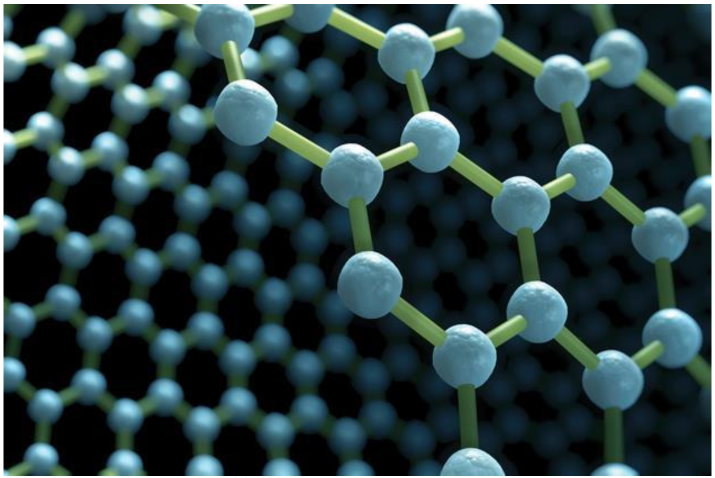
Setting aside the potential for a global AI calamity, there remains the risk of widespread instability resulting from the displacement of human workers by robotics and AI. A recent study by researchers at Oxford and Yale universities surveyed over 350 of the world's leading experts on AI. Experts projected a 50% chance of AI surpassing human performance on most job-related tasks by 2050.[13] Notably, the experts believed that automation is likely to cut across labor categories - lawyers are just as likely to be replaced by AI as employees at fast food chains. It is also noteworthy that these projections could actually underestimate the rate of change. Respondents thought it would take around 12 years for a computer to defeat a human master at the game of Go, but that event happened just one year later, in March of 2016.[14] It is highly likely that robotics and AI will permeate almost every sector of daily life, economic activity, and defense within 30 years.

As previously noted, experts project that a growing number of jobs will become automated over the coming decades. Those most at risk include commercial vehicle drivers, factory workers, and service sector employees[15]. For example, the automation of customer service has the potential to eliminate millions of jobs in call centers across much of the developing world.[16] Governments are just beginning to grapple with the potential dangers of this emerging, massive economic realignment. However, many political leaders lack the technical background to fully understand the pace of technological development in this area and the full scope of the potential disruption rapid automation could cause, especially in regions of the world that are already teetering on the edge of instability.

In addition to these risks, it is likely that military applications of robotics and AI will proliferate among both near-peer competitors and other adversaries of the United States. It is likely that many future adversaries will not share our reluctance to give robots full autonomy to use lethal force. This could put U.S. forces at a disadvantage, as the decision cycle of a fully automated weapon system will be many times faster than any human-in-the-loop system. In addition, the decline in U.S.-based manufacturing of microprocessors, sensors, and other autonomous system components could open the Army and its sister services to a significant vulnerability from cyberattack. For example, in 2012, researchers identified backdoors in Chinese-made microchips used by the U.S. military.[17] The U.S. government responded by issuing directives banning the use of Chinese components in key networking systems. However, it is unclear whether the Department of Defense has a comprehensive strategy for ensuring that defense contractors aggressively vet foreign suppliers and test for backdoor exploits.

Advanced Materials and Manufacturing Technologies

Advanced materials and manufacturing methods are undergoing rapid growth, with innovation driven by large investments in industries ranging from automotive design to medical devices. The global market for advanced materials, such as graphene, and advanced manufacturing methods, such as 3D printing, is likely to reach $400 billion to $1.1



Source: www.chemistryworld.com

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[13] Grace, K., Salvatier, J., Dafoe, A., Zhang, B., & Evans, O. (2017). When will AI exceed human performance? Evidence from AI experts. Manuscript in press. Pre-print available from https://arxiv.org/pdf/1705.08807.pdf.

[14] https://phys.org/news/2016-03-google-game-korean-master.html

[15] https://www.pwc.co.uk/economic-services/ukeo/pwcukeo-section-4-automation-march-2017-v2.pdf

[16] https://www.economist.com/news/international/21690041-call-centres-have-created-millions-good-jobs-emerging-world-technology-threatens

[17] https://www.crn.com.au/news/chinese-backdoors-discovered-in-us-military-chips-302810

trillion by the mid-2020s.[18] Certain applications, such as quantum dots[19] used for high-fidelity video displays and other applications, are likely to see particularly rapid growth as advances in manufacturing enable nanomaterials to be produced reliably at industrial scales.

Advanced materials includes a broad range of innovations, including nanomaterials, ceramics, and "smart materials" that are capable of self-healing and other functional capabilities. Graphene, a nanomaterial comprised of a two-dimensional layer of carbon atoms, has attracted considerable interest since it was first produced in 2004. For example, replacing current silicon semiconductors with graphene could enable significantly smaller, faster electronic chips for computers and other electronic applications, including distributed sensors in the emerging Internet of Things.[20] A major barrier to graphene application has been the inability to tune graphene composites to produce materials that perform reliably and that can be manufactured at scale. Researchers at the U.S. Department of Energy's Ames Laboratory recently made strides towards resolving this barrier by demonstrating a mechanism for modifying graphene's electronic band structure through controlled introduction of metal atoms.[21] This represents an important step toward making graphene a practical material for real-world applications.

Advances are also being made in novel techniques for producing nanomaterials from recycled waste. Researchers at Qilu University of Technology in Shandong, China, have developed a method for turning leaves and other biomass waste into a porous carbon material that acts as a supercapacitor.[22] Electrochemical testing found that the material has a specific capacitance (a measure of the ability of a material to store an electric charge) of 367 Farads/gram, a value three times higher than some graphene supercapacitors.

The Liberator, a 3D-printed working firearms. Source: www.3dprint.com

Over the next 30 years, nanomaterials and other novel materials such as metallic foams and ceramic composites will be found in clothing, building materials, vehicles, roads and bridges, and countless other objects. The Army will be able to leverage advanced materials to produce lighter, stronger body armor, more efficient vehicles and shelters, and more robust batteries and renewable energy systems. Advanced materials also present potential risks for the Army, and U.S. national security more broadly. The environmental impacts of nanomaterial pollutants are poorly understood, and it is possible that these materials could present health risks to Soldiers and civilians through long-term exposure. A team of researchers at Edinburgh University found that gold nanoparticles present in the air work their way into the bloodstream within 15 minutes, and persist in the body for months.[23] Aside from concerns over contamination, it is also highly likely that future adversaries will benefit from applications of advanced materials for their own military capabilities. Materials science has become globalized, and economic incentives are likely to create a large market for materials that exists outside of U.S. export controls.

Within the realm of advanced manufacturing, 3D printing (or, more broadly, additive manufacturing) is likely to continue growing rapidly over the next 30 years. Additive

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[18] MGI

[19] A recent market analysis of the nanotechnology sector found that the market for quantum dots is likely to grow at a compounded annual growth rate (CAGR) of 41.3% through 2021. https://www.bccresearch.com/market-research/nanotechnology/quantum-dots-global-market-report-nan027e.html

[20] http://www.mckinsey.com/industries/high-tech/our-insights/the-internet-of-things

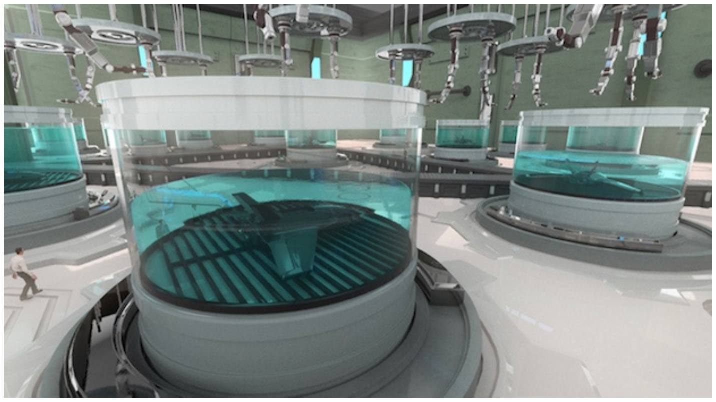
[21] Minsung Kim, Michael C. Tringides, Matthew T. Hershberger, Shen Chen, Myron Hupalo, Patricia A. Thiel, Cai-Zhuang Wang, Kai-Ming Ho. Manipulation of Dirac cones in intercalated epitaxial graphene. Carbon, 2017; 123: 93 DOI: 10.1016/j.carbon.2017.07.020

[22] American Institute of Physics. (2017, August 29). High-tech electronics made from autumn leaves: New process converts biomass waste into useful electronic devices. ScienceDaily. Retrieved August 30, 2017 from www.sciencedaily.com/releases/2017/08/170829113813.htm

[23] https://www.newscientist.com/article/2128923-pollution-nanoparticles-may-enter-your-blood-and-cause-disease/

manufacturing is already established in industrial settings, and the widespread availability of low-cost 3D printers is laying the groundwork for distributed network of small-scale manufacturers. Companies like Shapeways, Voodoo Manufacturing, and Sculpteo are providing on-demand 3D printing services to consumers and businesses. Researchers are also developing so-called "4D printing", which uses additive manufacturing techniques to create objects that can change shape in response to heat, light, mechanical force, or electrical signals. Scientists at Singapore University of Technology and Design have recently discovered a way to rapidly produce 4D printed materials using memory polymers that change shape when heat is applied.[24] 4D printing could enable self-assembling shelters, flat-pack robots that self-assemble on delivery, and other transformative applications.

3D printing also holds tremendous potential in the medical domain. 3D printed prosthetics are becoming more widely available, offering hope to millions of amputees who lack access to traditional prosthetics.[25] In addition to lower cost, 3D printed prosthetics offer far greater individual customization of fit and function. The next major advance in biomedical applications of 3D printing is likely to come in the form of printed organs and other biological tissue. In June of 2017, a team of scientists at South Korea's Pohang University of Science and Technology demonstrated a technique for 3D printing human skin using a process significantly faster and more efficient than existing techniques.[26] Other laboratories around the world are working on 3D printing organs, including cartilage printed from stem cells.[27]



BAE Systems and Scotland-based Cronin Group PLC are working on technology for "growing" drones by assembling them at the molecular level. Source: whttp://bgr.com/2016/07/08/chemical-drones-uk-scientiests/

By 2047, it is highly likely that 3D printers will be able to print objects with integrated electronic circuits, batteries, and other complex components. People will be able to print tools, electronics, replacement parts, medical devices, and other products on demand, customized to their wants and needs. Military logistics will likely become streamlined, as equipment and supplies will be printed directly at their point of use. Objects will become information, and digital piracy could replace shoplifting. The proliferation of low-cost 3D printing technology also poses potential threats. It is highly likely that terrorists and criminal organizations will print weapons, sensors, and other equipment using raw materials that are difficult to track on the open market. In fact, 3D printed firearms are already generating significant public controversy and new challenges for law enforcement.[28]

Energy Production, Harvesting, Storage, and Distribution

The world still largely runs on fossil fuels, but clean energy is slowly working its way into the mix. The share of renewables in global energy consumption grew from 17.9% to 18.3% from 2012 to 2014.[29] Global investment in renewables (excluding hydropower) fell 23% from a high point in 2015 to $241.6 billion in 2016. However, the amount of new capacity installed reached a record 138.5 GW in that year.[30]

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[24] https://www.newscientist.com/article/2127713-4d-printing-makes-objects-that-assemble-themselves-when-heated/
[25] https://www.theguardian.com/technology/2017/feb/19/3d-printed-prosthetic-limbs-revolution-in-medicine
[26] https://www.sciencedaily.com/releases/2017/06/170611204318.htm
[27] Duong Nguyen, Daniel A. Hägg, Alma Forsman, Josefine Ekholm, Puwapong Nimkingratana, Camilla Brantsing, Theodoros Kalogeropoulos, Samantha Zaunz, Sebastian Concaro, Mats Brittberg, Anders Lindahl, Paul Gatenholm, Annika Enejder, Stina Simonsson. Cartilage Tissue Engineering by the 3D Bioprinting of iPS Cells in a Nanocellulose/Alginate Bioink. Scientific Reports, 2017; 7 (1) DOI: 10.1038/s41598-017-00690-y
[28] https://www.wired.com/2016/02/someone-mostly-3-d-printed-a-working-semi-automatic-gun/
[29] Report of the Secretary-General, "Progress towards the Sustainable Development Goals", E/2017/66
[30] Global Trends in Renewable Energy Investment 2017. UN Environment Programme and Bloomberg New Energy Finance.

Source: Shutterstock

Novel extraction techniques have made new oil and gas reserves accessible. One-third of U.S. energy production now comes from natural gas, followed by 28% from oil.[31] The U.S. is currently a net energy importer. However, most scenarios in the EIA's Annual Energy Outlook 2017 project the U.S. becoming a net energy exporter as petroleum liquid imports decline and natural gas exports rise.[32]

On the renewables front, the median installed price of solar photovoltaics (PV) dropped in 2015 by 5% for residential systems[33] and 12% at the utility-scale.[34] This represents the sixth straight year of significant cost declines. Continued cost reductions are expected, putting solar costs on par with those of fossil fuels in many U.S. states. Interestingly, the cost of the panels themselves has leveled off after a steep decline from 2008 to 2012. That means most of the recent installed cost declines have come through "soft costs," including the equipment that converts DC power from the panels to AC for the grid, customer acquisition, and regulatory compliance.

Looking out to 2047, the International Energy Agency's World Energy Outlook 2016 report sees renewables and natural gas fulfilling much of the global energy demand growth. It predicts little growth in coal consumption but continued rise in oil consumption. Alternatives for oil in ground freight and air transportation as well as petrochemicals are proving difficult to develop. Demand will increase for those uses, while biofuels and electric vehicles (EVs) will level off oil demand in the passenger vehicle space.[35] If countries abide by pledges from the Paris agreement, the report predicts that, by 2040, 37% of power generation will come from renewables, 150 million EVs will be on the road (up from 1.3 million today), and CO2 emissions from the energy sector will grow by an average of 0.5% annually.

Progress in producing cheaper, more efficient solar technology is steady. For example, researchers are developing materials that can convert a broader spectrum of the sun's light to energy. A group from George Washington University, funded by Advanced Research Projects Agency-Energy (ARPA-E) recently reported on a multi-layered device that uses lenses to concentrate sunlight onto tiny solar cells. It can utilize energy from long-wavelength photons that conventional cells cannot, and it works with 44.5% efficiency, compared with 25% efficiency of today's most common solar cells.[36] In terms of creating liquid fuels, scientists at CalTech and other institutions are developing "solar fuels" through processes that mimic photosynthesis. The technology uses a catalytic membrane that absorbs sunlight, CO2, and water to secrete liquid or gas fuels. One of the more promising solar technologies is an "artificial leaf" being developed by Dr. Daniel Nocera at Harvard University. The process employs sunlight-activated catalysts to split water into hydrogen and oxygen. Engineered bacteria then combine the hydrogen with carbon dioxide to produce liquid fuel. Dr. Nocera's lab reports that their method works 10 times better than an average plant's natural ability to convert sunlight to energy.[37] Other potentially significant sources of alternative energy include: biofuels, geothermal, and next-generation nuclear, in which a closed system continually recycles waste.

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[31] U.S. Energy Information Administration Monthly Review, April 2017.
[32] U.S. Energy Information Administration, Annual Energy Outlook 2017.
[33] Barbose, GL and Darghouth, NR. Tracking the Sun IX. Berkeley Lab.
[34] Bolinger, M and Seel, J. Utility-Scale Solar 2015. Berkeley Lab.
[35] World Energy Outlook 2016. International Energy Agency.
[36] Lumb MP et al. "GaSb-Based Solar Cells for Full Spectrum Energy Harvesting." Advanced Energy Materials, 2017.
[37] https://www.technologyreview.com/s/603275/the-biggest-clean-energy-advances-in-2016/

Energy storage technology is critical to making solar and wind feasible and cost-competitive in the energy mix. Storage for these intermittent power sources can take many forms, including energy stored in water pumped uphill or in compressed air, which can later be released to turn turbines. However, significant advances are occurring in battery technology. The co-inventor of the lithium-ion battery, with colleagues at the University of Texas at Austin, recently reported on new all-solid-state cells that have three times the energy density as lithium-ion batteries. In addition, the new batteries are noncombustible, have a long life, and charge and discharge quickly.[38] According to the researchers, "the glass electrolytes allow for the substitution of low-cost sodium for lithium. Sodium is extracted from seawater that is widely available."[39] Integrating this technology into desalination plants could offer an efficient solution for both energy and fresh water demands. Flow batteries are another promising technology. These batteries store energy in electrolyte solutions in tanks, rather than using solid electrodes. A research team recently developed an inexpensive, non-toxic solution for a flow battery that loses only 1% its capacity after 1,000 discharge/recharge cycles.[40]

Another key area undergoing transformation is energy transmission. Transitioning to a smart grid can improve energy efficiency, allow for the onboarding of new and distributed forms of power and storage, and improve resiliency to attacks and natural disasters. A $7.9 billion U.S. Department of Energy program is funding the deployment of smart grid updates around the country.[41] And the incorporation of artificial intelligence into grids is in the R&D phase. The Schoonschip project, currently being built in Amsterdam, will be a neighborhood run on AI-enabled, smart-grid technology for 100 residents.[42]

According to a report in support of NATO defense planning, energy costs comprise a large portion of military budgets, so development and adoption of efficiency measures and alternative, renewable energy sources may pay for themselves relatively quickly. Additionally, an updated grid that's more resilient to natural disasters and impervious to cyber-attacks can help strengthen national security; a grid incorporating more renewables is inherently more distributed and secure. Finally, battery technology may be of strategic importance to NATO as military demand for portable power increases. Better battery design and efficiency reduces battalion weight and diesel generator fuel needs.[43]

The ability for the U.S. to produce more power domestically means that it can shape its foreign policy independently of how it consumes energy. However, even as America moves toward energy security, the market will remain globally interconnected; instability in other areas of the world can have ripple effects on the U.S. economy and military operations.

Biomedical Science and Human Augmentation

Over the next 30 years, it is highly likely that human health and performance will be radically transformed by multiple, converging lines of innovation. Health care analytics, supported by artificial intelligence, will give physicians powerful new tools for developing a holistic picture of patient health. Wearable and ambient sensors will integrate with mobile devices, giving patients and physicians alike unprecedented capabilities for monitoring health and identifying interventions that can ward off diseases before they manifest. Genetic science is likely to drive the development of personalized pharmaceuticals that deliver effects that are tailored to individual physiology, improving treatment outcomes while producing fewer side effects. Physical and cognitive augmentation technologies are likely to extend the human "health span" and enable people to remain productive well into their senior years. At the same time, the cost of advanced medical care will stress many national health care systems and trigger rising inequality in access to life-saving treatments. The coming medical

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[38] Braga MH et al. "Alternative strategy for a safe rechargeable battery." Energy and Environmental Science, 2017.

[39] https://news.utexas.edu/2017/02/28/goodenough-introduces-new-battery-technology

[40] Beh ES et al. A Neutral pH Aqueous Organic/Organometallic Redox Flow Battery with Extremely High Capacity Retention. ACS Energy Letters. 2017.

[41] https://energy.gov/oe/information-center/recovery-act-smart-grid-investment-grant-sgig-program

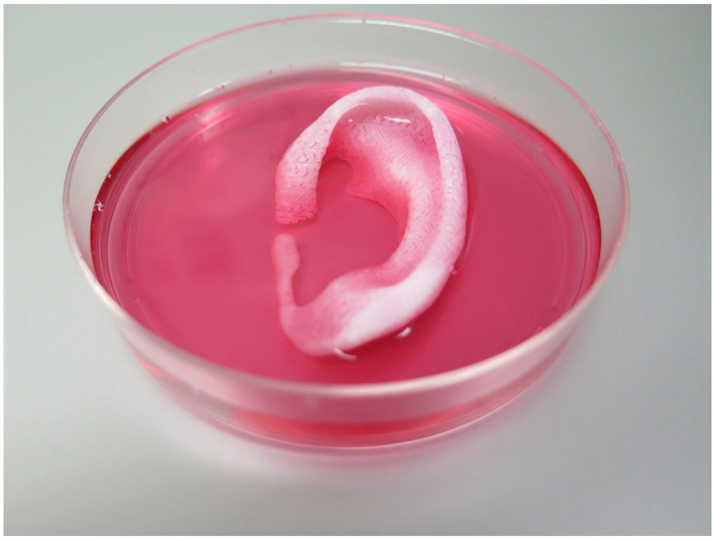
[42] http://schoonschipamsterdam.org/en/

[43] Technology Trends Survey HQ Supreme Allied Commander Transformation, Defence Planning Policy and Analysis Branch, May 2013.

revolution will also enable people to remain healthy and productive for decades longer, amplifying competition for jobs between older and younger workers and creating additional strain on social safety nets.

Analytics has begun to shape medicine in a profound way, and health care analytics has become a hotbed of startup innovation. For example, Princeton-based eCare21 remotely collects continuous streams of health data from thousands of senior citizens using smartphones, activity monitors, and other networked wearable sensors. The company fuses these data feeds into rich data dashboards that seniors, caregivers, and their loved ones can use to monitor health status and make informed medical decisions.[44]

As with other examples of "big data" the challenge in medical analytics lies in extracting useful insights from the massive amounts of data that are increasingly becoming available. Artificial intelligence is likely to play an important role in this regard. The market for AI applications in health care and life sciences is expected to grow by 40 per year over the next five years, reaching $6.6 billion by 2021.[45] By 2047, advances in deep learning and other unsupervised learning techniques for training AI are likely to drive the development of automated diagnostic agents that perform as well as human physicians in detecting disease. AI-based tools with access to massive amounts of data, including genetic makeup and population statistics, could provide better-informed treatment recommendations to doctors and patients. PathAI, a health care AI startup founded by faculty from MIT and CalTech, won a competition in April 2016 pitting artificial intelligence against human pathologists in detecting breast cancer.[46] PathAI's bot had an error rate of 7.5 percent, about double the human expert's rate of 3.5 percent. The team was also able to demonstrate that teaming a human pathologist with the AI diagnostic agent reduced the human expert's error rate by 85 percent.


Complete ear structure made using a 3D bioprinter. Source: Wake Forest Baptist Medical Center.

Regenerative medicine is another example of a rapidly maturing biomedical application. Regenerative medicine uses genetic material from stem cells or engineered DNA or RNA to rebuild damaged tissues in the body. It represents one branch of the broader domain of personalized medicine, which leverages deep understanding of the human genome, advanced modeling and analytics, and principles from bioengineering to produce preventive and corrective treatments that are custom-designed to fit with an individual's physiological makeup. Regenerative medicine is a rapidly growing field, with an annual market growth rate of 26%, and a projected market size of $101 billion by 2022.[47] Several of the key players in regenerative medicine are Shire Pharmaceuticals, Genzyme, and Advanced Cell Technology.

One of the major challenges with regenerative medicine is delivering treatment precisely to affected tissues. Most of the focus has been either on implanting cells that have been engineered and cultured outside the body, or using genetically viruses to deliver DNA "patches" to induce desired effects within the body. Both approaches are costly, imprecise, and prone to creating unwanted side effects (e.g., "transfection" by viruses of modified DNA to otherwise healthy tissues).

A team of scientists from the Ohio State University has addressed this challenge, recently announcing a new technique for in vivo cell reprogramming that could offer

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[44] https://www.forbes.com/sites/mikemontgomery/2016/10/26/the-future-of-health-care-is-in-data-analytics/#3243f3903ee2
[45] https://www.cnbc.com/2017/05/11/from-coding-to-cancer-how-ai-is-changing-medicine.html
[46] Ibid.
[47] http://www.reuters.com/brandfeatures/venture-capital/article?id=11233

USSOCOM TaLOS exoskeleton concept. Source: www.futurism.com

a new option for delivering regenerative treatments.[48] The technology involves applying a chip that creates "nanochannels" in tissue using an intense, focused electric charge. A therapeutic package of DNA or RNA can be precisely delivered through these channels into diseased tissue. Animal tests have shown efficacy in healing brain lesions and peripheral artery blockages. Describing the technique, Dr. Chandan Sen, co-lead of the project, said, "[the procedure] takes just a fraction of a second. You simply touch the chip to the wounded area, then remove it. At that point, the cell reprogramming begins."

If biomedical science promises to optimize human health, human augmentation technologies offer to expand the envelope of what our minds and bodies can achieve. While human augmentation remains more in the realm of science fiction, there are several recent developments that point to promising applications by 2047. Exoskeleton technology has advanced rapidly in the past five years, driven by progress in battery technology, materials, control algorithms, and sensor technology. Much of this development has been fueled by defense-related investments. Perhaps the most ambitious defense exoskeleton effort is the U.S. Special Operations Command (USSOCOM) Tactical Light Operator Suit (TALOS) program. Launched in 2013, TALOS envisioned a full-body exoskeleton that would provide ballistic protection, integrated heating and cooling, a heads-up display, oxygen and hemorrhage controls, along with increased physical performance.[49] It is unclear whether the TALOS design specification can be met with current technologies, but the funding USSOCOM is applying to the problem (estimated at $80 million) should significantly advance the state of the art. Companies including Ekso Bionics, SuitX, and BTemia have entered the exoskeleton space in recent years with systems designed to restore mobility to individuals suffering from paralysis and reduced mobility. Applications are also

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[48] http://www.nature.com/nnano/journal/vaop/ncurrent/full/nnano.2017.134.html?foxtrotcallback=true

[49] https://www.digitaltrends.com/cool-tech/us-military-readies-iron-man-style-suit-for-deployment/

beginning to emerge in heavy industry, construction, and other sectors.

Exoskeletons face significant technical hurdles, such as providing power for extended use without tethering to a large, immobile power source. However, most of these barriers reflect engineering challenges that are likely to be solved by 2047. It is likely that exoskeletons will be used by military forces by that time. At a minimum, exoskeletons could significantly improve ordnance handling, vehicle maintenance, and other tasks involving heavy materials. It is possible that they could be used to enhance performance of infantry units and other front-line forces by 2047, if technical progress accelerates. Exoskeletons could enable Soldiers to carry significantly greater loads, increase mobility, and enable small units to carry heavy weapons.

Augmentation technologies could also enhance mental performance by 2047, though progress on this front is less certain relative to the physical domain due to the more fundamental state of neurocognitive research. Nootropics – molecules that enhance mental acuity – are currently available on commercial and "gray" markets, but there are no substances currently approved by any government specifically for the safe enhancement of cognitive performance in otherwise healthy individuals.

Pharmaceuticals such as Modafinil have become increasingly popular for neuroenhancement on college campuses and in the workplace, and a recent meta-analysis of efficacy established that these compounds do have the ability to significantly boost focus and memory retention.[50] However, there have been few studies on long-term side effects of off-label use of pharmaceuticals as nootropics. There is also a growing market for herbal supplements claiming to boost cognitive performance. The global market for these products is projected to top $6 billion by 2024, driven largely by demand in the United States.[51] At present, the science on most supplements is considered weak at best.[52] However, it is possible that safe and effective cognitive enhancement could be available by 2047. The key technical barrier is a better understanding of brain neurophysiology and mechanisms of action that can safely be modulated by pharmaceutical molecules. For instance, the mechanism by which Modafinil boosts focus and memory is currently unknown.[53]

A more troubling possibility is that progress in the understanding of human genomics could lead to "designer babies" engineered for desirable mental and physical characteristics. While the complex interaction between genes and expressed characteristics (e.g., genotype vs. phenotype) is currently beyond our ability to precisely manipulate, it is possible that some form of performance-enhancing genetic modification could be available by 2047.

The enormous therapeutic potential of genomics, coupled with the exponentially declining cost of gene editing techniques such as CRISPR, has created fertile ground for rapid technological progress in genetic engineering. China is at the forefront of much of this research. In 2017, Chinese scientists successfully removed genetic mutations from viable human embryos[54] and created genetically engineered dogs with double the normal muscle mass.[55] These advances skirt the border between therapeutic breakthroughs and more frightening images of genetically-engineered "super soldiers". At present, there is very little international oversight of genetic engineering work in humans, and no global framework for regulating this kind of research. Given the progress that has already been demonstrated, it seems likely that genetic engineering could be applied to enhance human performance by 2047. The question is, whether all nations will agree on appropriate ethical constraints.

Quantum Computing

In recent years, quantum computing and communications have moved largely out of the theoretical and into the plausible. MIT's Technology Review named "practical quantum computing" as one of its 10 breakthrough

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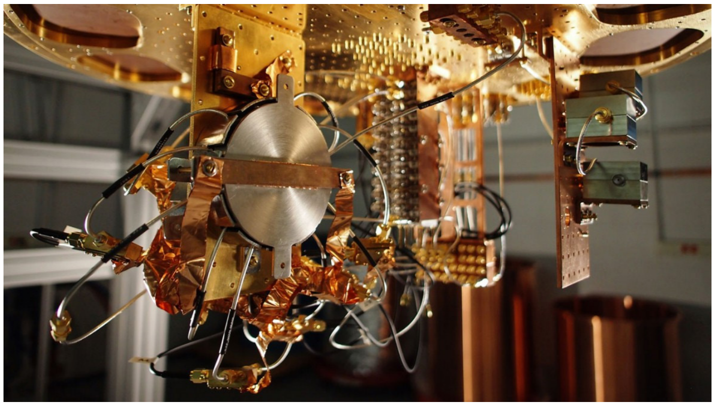
[50] https://www.theatlantic.com/health/archive/2015/08/the-rise-of-work-doping/402373/
[51] https://www.credenceresearch.com/press/global-nootropics-market
[52] https://www.sciencedaily.com/releases/2013/04/130415151439.htm
[53] https://www.scientificamerican.com/article/a-safe-drug-to-boost-brainpower/
[54] http://www.popularmechanics.com/science/a25626/chinese-scientists-genetically-modify-human-embryos/
[55] https://www.technologyreview.com/s/542616/first-gene-edited-dogs-reported-in-china/



A quantum computer being developed by Google. Source: MIT Technology Review

technologies for 2017.[56] While quantum computing has been "right around the corner" for over a decade, recent breakthroughs combined with government and venture capital investment, are pushing this technology closer to the tipping point. It is highly likely that quantum computers will surpass the capabilities of classical computers on problems such as factoring very large numbers[57] within the next decade. Therefore, it is likely that this technology will replace current computing technologies in many critical areas (e.g., cryptography) by 2047.

In a classical computer, a bit has a value of 0 or 1 and acts as an on/off switch. But a quantum bit, or qubit, in quantum computers may represent both 0 and 1 simultaneously, and the state of one qubit can depend on the state of another. Because of these quantum physics principles—superposition and entanglement, respectively—qubits are more sophisticated switches that can perform multiple calculations at once. Hence, quantum computers will be able to make rapid calculations on massive datasets and solve problems that today's computers cannot.

Innovators are on the cusp of surpassing a threshold coined "quantum supremacy," at which a quantum computer's capabilities exceed those of a classical computer. Scientists calculate that quantum supremacy will be achieved with a system containing around 50 qubits. IBM opened a 5-qubit quantum-computing platform to the public for experimentation in summer 2016, and the company recently announced that it had built and tested 16 and 17-qubit systems.[58] IBM plans to build a roughly 50-qubit system within the next few years[59], while a Google team aims to build a 49-qubit integrated circuit by the end of 2017.[60]

Governments, industries, and investors have recognized the need for research and development in this potentially transformative field. Lockheed Martin helped establish quantum computing research centers at the University of Maryland and the University of Southern California.[61] According to a 2017 Deloitte University Press report, venture capital investors have poured $147 million into quantum computing startups in the last three years, and globally, governments have invested $2.2 billion in quantum computing research.[62]

Quantum computing can generate solutions to complex problems with unprecedented speed and sophistication in a wide range of fields. It has the potential to accelerate the discovery of new medicines and materials, optimize global supply chains, make artificial intelligence more powerful, and improve financial and climate modeling.[63] Perhaps most consequentially, quantum computing can help protect individuals and institutions from cybercrime. The inability of ordinary computers to factor very large numbers underpins many of today's encryption schemes, such as those for bank cards and online privacy. Last year, however, researchers from the University of Innsbruck and MIT implemented a quantum computer algorithm to solve this factorization problem in a scalable manner.[64] In addition, while quantum computing may crack previously unbreakable codes, it may also provide unbreakable

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[56] https://www.technologyreview.com/s/603495/10-breakthrough-technologies-2017-practical-quantum-computers/

[57] Most modern cryptographic techniques, such as RSA encryption, rely on factoring large prime numbers.

[58] https://researchweb.watson.ibm.com/ibm-q/

[59] https://www-03.ibm.com/press/us/en/pressrelease/51740.wss

[60] http://spectrum.ieee.org/computing/hardware/google-plans-to-demonstrate-the-supremacy-of-quantum-computing

[61] https://www.washingtonpost.com/business/on-it/lockheed-martins-bet-on-quantum-computing/2014/03/15/9db067f8-a61b-11e3-84d4-e59b1709222c_story.html

[62] Schatsky D and Puliyakodil RK. "From fantasy to reality: Quantum computing is coming to the marketplace." Signals for Strategists. Deloitte University Press, 2017.

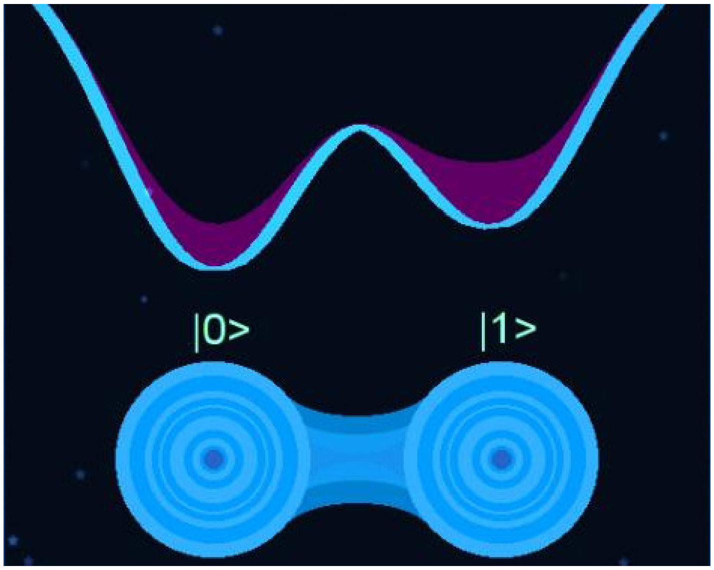
[63] http://research.ibm.com/ibm-q/learn/quantum-computing-applications/

[64] Monz T et al. Realization of a scalable Shor algorithm. Science, 2016.

replacements. Researchers at the Russian Quantum Center recently developed a quantum-safe blockchain, which could secure sensitive digital information and cryptocurrencies such as Bitcoin.[65] Microsoft and others are developing new encryption techniques that could secure data against both classical and quantum computers[66], but these techniques have yet to be deployed.

Researchers are also making significant advances in quantum communications and have produced several proof-of-concept technologies in the past year. Quantum communication is considered to be extremely secure because any attempt to intercept data would be evident to the sender, and the message could hence be altered or deleted. China is on its way to launching the world's first quantum network, known as the Jinan Project. Hundreds of users from China's military, government, finance, and electricity sectors will send messages on this network, which will stretch more than 2,000 km.[67] In more-experimental efforts, a group of Chinese researchers used a satellite to beam entangled pairs of photons to three ground stations, each more than 1,200 km apart.[68] Another Chinese team recently made the first step toward underwater quantum communication, sending entangled photons a short distance (3 meters) through seawater.[69] Additionally, a Canadian team sent a quantum-encrypted message through the air over a city, marking the first successful real-world test of its kind.[70]

One of the largest hurdles to overcome in quantum computing is controlling "quantum decoherence." This refers to the errors that occur in a system when it interacts with its environment; quantum superposition and entanglement are delicate conditions that can be disturbed by vibrations, electric fields, and other environmental factors. A limited amount of error correction is possible, but the additional computing power it requires may render it impractical in larger systems. The problem is particularly acute in communications applications, as signals are susceptible to turbulence in air or light-absorbing properties of seawater.



Qudits could be the true brakthrough in quantum computing. Source: https://www.eurekalert.org/pub_releases/2016-12/miop-teg121216.php

A lab at Delft University of Technology is working on a solution to this problem that involves manipulating a recently discovered quasiparticle.[71] As another approach, "qudits", rather than qubits, may enable more efficient and error-tolerant computation. In a qudit, a photon may have a superposition of more than two states, and a few qudits could do the same work as many more qubits. An international team of researchers recently created a microchip containing two qudits, each with 10 states.[72]

The power of quantum computing shows great potential in many aspects of military operations. Security of information and communications networks can improve through quantum applications. Improved logistics may mean that deployed troops can receive exactly the right support at exactly the right time and place. And the cost of weapons testing, particularly for debugging software,

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[65] Kiktenko EO et al. Quantum-secured blockchain. arXiv:1705.09258 [quant-ph], 2017.
[66] https://www.technologyreview.com/s/539441/securing-todays-data-against-tomorrows-quantum-computers/
[67] https://phys.org/news/2017-08-china-world-quantum-network.html
[68] Yin J et al. Satellite-based entanglement distribution over 1200 kilometers. Science, 2017.
[69] Ji L et al. Towards quantum communications in free-space seawater. Optics Express, 2017.
[70] Sit A et al. High-Dimensional Intra-City Quantum Cryptography with Structured Photons. Optica, 2017.
[71] https://www.technologyreview.com/s/603495/10-breakthrough-technologies-2017-practical-quantum-computers/
[72] Kues, M et al. On-chip generation of high-dimensional entangled quantum states and their coherent control. Nature, 2017.

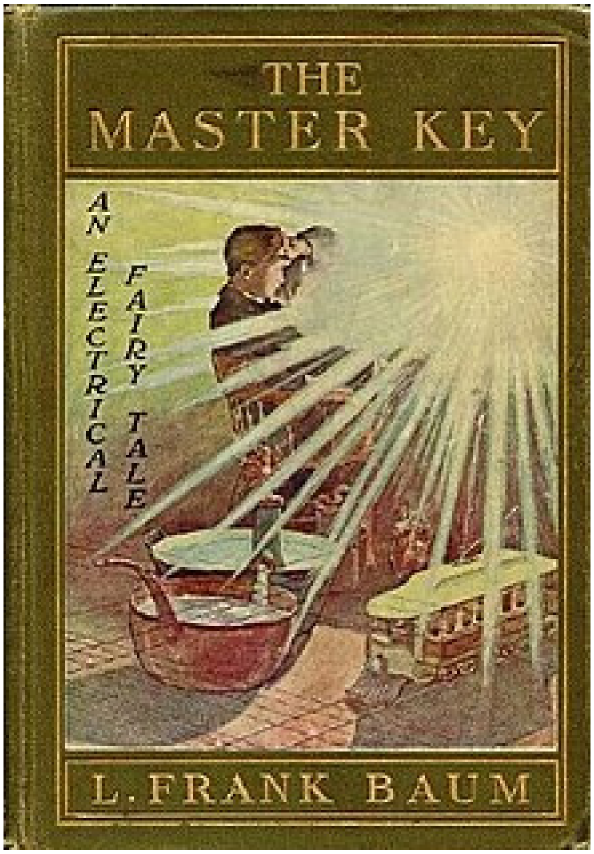
could come down.[73] The U.S. Department of Defense and the Office of the Secretary of Defense are investing in basic and applied quantum information science with a focus on precision navigation, precision timing, and secure quantum networks.[74]

Failure to keep up with advances in quantum computing and communications would present fundamental security and privacy risks. Much of today's data encryption is trivial for quantum computing. The National Security Agency has begun advising federal agencies and their contractors on transitioning to "post-quantum cryptography" so that encrypted data remains secure against quantum computing systems.[75] Agencies and companies need to safeguard data against such attacks before they become reality to avoid having to delete data or disconnect devices from networks.

Mixed Reality and Digital Mimicry

Mixed reality is the fusion of real and virtual worlds through immersive technologies including virtual reality (VR) and augmented reality (AR). The vision of mixed reality has deep roots. L. Frank Baum, author of The Wizard of Oz, wrote an illustrated novel in the year 1901 that described a device called the "Character Marker", a set of glasses that would superimpose a letter over anyone the wearer viewed that signifying his or her moral standing.[76] Mixed reality has been a fixture of science fiction for decades, but until recently, the technical limitations of computer graphics and visual display technology prevented the creation of truly immersive digital-physical experiences. However, this is changing, and mixed reality is undergoing a renaissance driven by three primary factors:

- Widespread availability of mobile devices with increasingly powerful graphics capabilities
- Development of toolkits that lower the barrier to entry for application developers



Cover of The Master Key, by L. Frank Baum, an illustrated novel written from 1901 with the first description of augmented reality. Source: Wikipedia

- Rapidly declining cost of head-mounted displays coupled with rapid improvement in display quality

The commercial potential of mixed reality is generating tremendous investment in VR and AR companies. Credit-Suisse recently published a market forecast predicting that total revenues for augmented and virtual reality products would top $600 billion by 2025.[77] For sake of comparison, this would equal the size of the current smartphone market. At present, commercial applications are largely focused on immersive gaming and educational visualizations. However, as technology continues to evolve it is likely that VR and AR will become standard technologies across a range of industries. For example, augmented reality could enhance a surgeon's ability to visualize internal

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[73] https://defensesystems.com/articles/2016/12/09/quantum.aspx
[74] "Advancing Quantum Information Science: National Challenges and Opportunities." National Science and Technology Council, 2016.
[75] https://arstechnica.com/information-technology/2015/08/nsa-preps-quantum-resistant-algorithms-to-head-off-crypto-apocolypse/
[76] http://www.historyofinformation.com/expanded.php?id=4698. It is interesting to note that the main character in this story, a teenage boy, receives the Character Marker from a demon.
[77] https://www.credit-suisse.com/ch/en/privatkunden/anlegen/besser-anlegen/news/articles/private-banking/2017/06/en/virtual-und-augmented-reality.html

anatomy and anticipate potential complications during delicate operations. Scopis, a Cambridge, Massachusetts-based developer of augmented reality software, is at the forefront of the emerging medical AR sector with an application that projects a mixed-reality overlay on a patient that helps doctors track surgical tools and implants.[78] VR and AR could also be used in construction and maintenance, overlaying schematics, technical data, and other information directly onto real-world objects.

Progress in mixed reality technology has been paralleled by dramatic improvements in the realism of computer-generated graphics and voice synthesis. Massive investments by the film and video game industries has fueled innovation in video and voice rendering, and the best computer-generated graphics are often indistinguishable from real-world scenes. While these developments have revolutionized entertainment, and opened new possibilities for immersive training simulations, there is also a growing risk that "digital mimics" could co-opt individual identity. For example, in 2015, researchers at the University of Alabama demonstrated that state-of-the-art voice verification technologies – the kind that are increasingly being deployed by banks and credit card companies – failed to reject up to 90% of fake voices.[79] This was especially alarming given that the research team used a commercial-off-the-shelf voice synthesis program. It is highly likely by 2047 that voice synthesis software will be capable of producing exceedingly high-fidelity imitations of specific individuals based on limited voice samples that will be freely available from online sources. It will be relatively easy for adversaries to imitate the voice of political, military, and cultural leaders using low-cost or free software. These tools could be used to manipulate public opinion and undermine government and defense operations.

The ability to synthesize convincing imitations of a specific individual's speech is just one part of the digital mimicry equation. Rapid progress is also being made in technology that renders high-fidelity, fully-animated models of specific people. In 2016, computer scientists in Germany demonstrated Face2Face, a tool that uses 3D face mapping technology to turn video recordings of real people into virtual "puppets" that can be controlled in real time.[80] A demonstration video on the project website shows an engineer controlling the facial expressions of George W. Bush, Barack Obama, Donald Trump, and Vladimir Putin. The technique uses high-resolution face scans that can reliably reproduce subtle movements of the mouth and eyes, creating convincing facial expressions that mimic emotional tone and speech. Coupled with the voice synthesis technologies discussed above, this technology points to a future in which physical identity is just as vulnerable to hacking as online presence is today. Furthermore, a team of computer scientists from the University of Nottingham have developed a neural network that can reconstruct a 3D image of a human face from a single photograph.[81] This technology could be used to rapidly model public officials and other key influencers. Off-the-shelf 3D modeling and animation software could be used to manufacture videos that undermine public communications or paint leaders in a negative light. Information warfare is likely to become significantly more complicated, as digital mimics take center stage in the battle for controlling strategic narratives.

Food and Water Technology

The green revolution of the mid-20th century expanded agriculture yields to an unprecedented degree. Despite recent "yield plateaus" of crops such as rice and wheat in some regions,[82] the proportion of undernourished people worldwide fell from 15% in 2000-2002 to 11% in 2014-2016.[83] Now experts forecast a need to increase food production levels an estimated 25-70% over current levels by mid-century[84]—and the challenge will be to do that while minimizing energy and land use, environmental degradation, and global warming potential. Meeting the world's fresh water needs will also become increasingly

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[78] https://www.engadget.com/2017/05/05/microsoft-hololens-becomes-an-ar-assistant-for-spinal-surgery/
[79] http://www.uab.edu/news/innovation/item/6532-uab-research-finds-automated-voice-imitation-can-fool-humans-and-machines
[80] http://www.graphics.stanford.edu/~niessner/thies2016face.html
[81] http://www.cs.nott.ac.uk/~psxasj/3dme/
[82] Grassini P, Eskridge KM and Cassman KG. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nature Communications, 2013.
[83] https://sustainabledevelopment.un.org/sdg2
[84] Hunter MC et al. "Agriculture in 2050: Recalibrating Targets for Sustainable Intensification." BioScience, 2017.

difficult. Already more than 2 billion people live in countries experiencing "excess water stress,"[85] and shifting weather patterns due to global warming will exacerbate drought in some regions.

Progress on improving global food and water security is occurring on many fronts. In the fields, farmers are employing "precision agriculture" practices. They're using sensors in their fields coupled with localized weather data and remote sensing images to apply just the right amount of water, fertilizer, and pesticides to their crops. Agriculture giant Monsanto acquired the Climate Corporation, a leader in field data management systems, in 2013 for approximately $1.1 billion. Farmers using Climate Corporation's tools can visualize weather, yield, field health, and nitrogen data for their fields, receive customized planting schedules, and connect a wireless device to their tractors to collect and transmit data about their activities.

In addition, scientists are genetically engineering crops that can withstand weather extremes. This is particularly important for staple crops, and researchers have developed several varieties of drought-tolerant rice, for example. They're also preserving crop genetic diversity by storing seeds in cryogenic facilities such as the Svalbard Global Seed Vault. This helps ensure the preservation of plant traits that farmers may need in order to grow food under different conditions in the future. Climate change has complicated this effort: warm weather and heavy rains in October 2016 caused water to enter the tunnel leading to the vault. However, it froze there and did not impact the seeds.

Several technologies for water security have proven themselves at scale in recent years. Desalination has long been written off as expensive and energy-intensive. As of 2015, a large, efficient reverse osmosis desalination facility in Israel was providing 20% of the water used by that country's households.[86] This plant produces water at a lower price than most desalination plants and consumes less energy than most plants of its scale. Orange County, California, utilities have made great strides in recycling waste water into ultra-clean potable water. It plans to increase its water reuse capacity to 130 million gallons per day[87]—water that it would otherwise discharge into the Pacific Ocean. On the lower-tech side, vertical fog-harvesting mesh nets can collect clean atmospheric water in areas with suitable climates, such as the coastal mountains of Chile, Peru, and Ecuador.[88] Researchers at MIT and their colleagues in Chile have worked to optimize the performance of these nets. They concluded that the ideal mesh was made from stainless steel filaments 3-4 times the thickness of a human hair and spaced apart at about twice that. Mesh performance also increases significantly when it's coated with a solution that allows the droplets to easily roll down and be collected before they can be blown away.[89]

Fog-harvestiing net. Source: HydraLife

In the coming decades, conventional farming may begin to give way to alternative methods of producing food, growing it in labs, cities, and even underground. The field of cellular agriculture is finding a toehold; scientists are using the latest in tissue engineering and synthetic biology to grow animal products without the animal. In 2013, Dutch professor Mark Post created the first "lab-grown" cell-cultured beef hamburger by growing thousands of muscle strands in

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[85] https://sustainabledevelopment.un.org/sdg6
[86] https://www.technologyreview.com/s/534996/megascale-desalination/
[87] https://www.ocwd.com/what-we-do/sound-planning/long-term-facilities-plan/gwrs-final-expansion/
[88] http://www.climatetechwiki.org/content/fog-harvesting
[89] Park K et al. Optimal Design of Permeable Fiber Network Structures for Fog Harvesting. Langmuir, 2013.

standard tissue culture flasks.[90] The cost of cell-cultured meat is still high, however, and more research is needed into lower-cost techniques that will enable this technology to scale. For example, muscle cells require a lot of surface area to grow at scale because they only grow to about 0.5mm in culture. 3D printed scaffolding may offer a solution. In addition, mechanical or electrical stimulation needs to be applied to the tissues to impart them with the desired texture.[91]

In other efforts to produce food in unconventional places, The Plant Chicago is a test bed for closed-loop, net-zero-energy urban farming—that can turn a profit—in an abandoned meatpacking facility. It features an aquaponics system that produces vegetables and fish, a brewery, bakery, and more. In The Plant, the waste from one process becomes raw material for another. Beneath the streets of Clapham on the outskirts of London, Growing Underground is producing salad greens with a hydroponics system in old tunnels. Entrepreneurs are also cultivating new, lower-impact sources of protein such as insects. Industrial cricket farms are cropping up around the U.S., and the insects are appearing in more and more food products.

Source: Popular Mechanics

Moving forward, the precision agriculture space will advance with the help of ultra-sensitive biological and electronic sensors.[92] Further, multispectral cameras on drones flying over farms may supplement satellite remote sensing for finer grained imagery of individual fields.[93] Plants with “hacked photosynthesis” may one day boost crop yields and cut down on the amount of land needed for food cultivation. Researchers recently engineered tobacco plants using enzymes from blue-green algae that converted CO2 to sugar faster than unaltered plants.[94]

The military stands to benefit from technologies that can increase the time between resupplies in the field. Air-to-water technologies, portable water-purification, and water reuse systems may be of particular importance. Looking more broadly, a report by the U.S. intelligence community notes that water challenges have brokered peaceful cooperation between otherwise hostile actors in the past.[95]

However, that same report notes that water issues are becoming more acute, and peaceful resolutions may give way to the use of water as leverage or weaponry. Further, the authors note, “water problems—when combined with poverty, social tensions, environmental degradation, ineffectual leadership, and weak political institutions—contribute to social disruptions that can result in state failure.” Climate change will continue to disrupt food production and water accessibility in the coming decades, and many countries may need international aid to stave off grave food and water shortages.[96] In an effort to improve food security, some large companies and nation-states are buying up cheap land abroad (particularly in Africa) to develop agriculture on it.[97] This “land grabbing” affects the livelihoods and food security of those in countries where land is being acquired.

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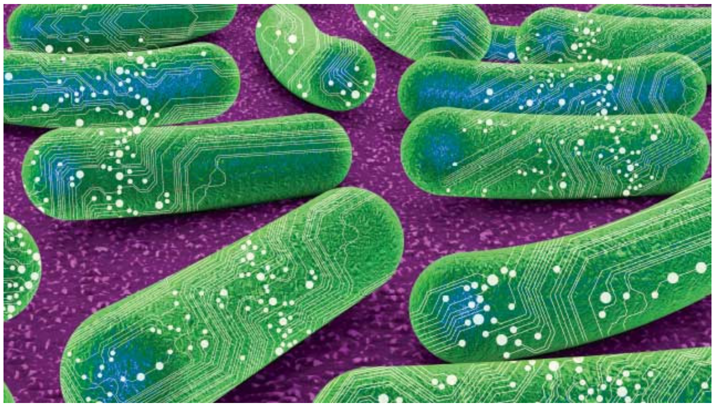
[90] http://www.new-harvest.org/mark_post_cultured_beef
[91] Post, MJ. Culture meat from stem cells: Challenges and prospects. Meat Science, 2012.
[92] European Commission Foresight Fiches: “Global Trends to 2030,” 2014.
[93] http://www.economist.com/technology-quarterly/2016-06-09/factory-fresh
[94] Lin MT et al. “A faster Rubisco with potential to increase photosynthesis in crops.” Nature, 2014.
[95] Global Water Security. Intelligence Community Assessment, February 2012.
[96] Future Land Warfare Report 2014. Commonwealth of Australia.
[97] https://www.cesi-italia.org/en/articoli/630/the-socio-political-impact-of-land-grabbing-in-africa-and-its-destabilising-effects

Synthetic Biology

Genetic engineering has been around since the 1970s, but despite the name the field largely relied on cutting and pasting genes rather than building from the bottom up. Now, the emerging field of synthetic biology is bringing engineering principles to biotechnology using computer modelling and DNA synthesis to write gene sequences from scratch. Falling costs and new gene editing tools like CRISPR are accelerating progress, and the global market is expected to reach $38.7bn by 2020.[98]

In the decade after the field's inception at the turn of the century, practitioners went from designing simple synthetic gene circuits to building the first fully synthetic genome in bacteria.[99] The group behind that breakthrough, led by geneticist and entrepreneur Craig Venter, has since created the world's smallest genome with just the genes essential to support life.[100] This March, the Synthetic Yeast Genome Project announced it had rewritten 5 of the 16 chromosomes of brewer's yeast,[101] a far more challenging prospect as yeast is a eukaryotic organism with more complex cellular physiology closer to that of higher animals. This synthetic yeast is a promising candidate for producing everything from biofuel to medicines and the researchers optimized the replaced chromosomes for industrial purposes.

While these efforts are focused on learning how to rebuild entire genomes, other scientists are designing artificial gene circuits that carry out novel functions. Using standardized DNA parts[102] – analogous to electronic components used to build integrated circuits – researchers have created everything from rudimentary biological computers[103] to bacteria that seek and destroy other microbes.[104] These techniques started out with well understood organisms like E. coli and yeast, but in recent years the approach has been extended to mammalian cells[105] and plants.[106] It has even been demonstrated that different strains of re-engineered organisms can be used to create multicellular environmental sensors[107] and cell-free gene circuits freeze-dried onto paper can be used to detect diseases like Zika.[108]



Source: The Scientist

These capabilities are beginning to spill over into industry. Early hopes that the field would soon be producing bulk chemicals like biofuels and plastics faded due to the high volume, low-price market dynamics for these products. Attention has shifted to "fine chemicals" that command high prices for small batches such as flavorings and fragrances such as the synthetic vanillin produced by Evolva.[109]
In recent years the scope of commercial products has started to expand. Companies like Gevo are using yeast to produce biofuel and plastic precursors while Novii, a joint venture between Amyris and Cosan, sells synthetic oils and lubricants. DSM has two joint ventures producing synthetic ethanol and succinic acid.[110] The landmark commercial success for synthetic biology came in 2014 when pharmaceutical giant Sanofi used genetically engineered

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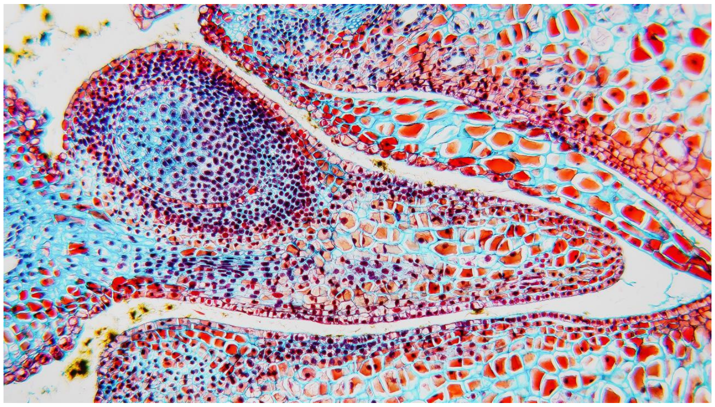
98 https://www.alliedmarketresearch.com/press-release/synthetic-biology-market-is-expected-to-Reach-38-7-Billion-Globally-by-2020.html
99 http://science.sciencemag.org/content/329/5987/52
100 http://science.sciencemag.org/content/351/6280/aad6253
101 http://science.sciencemag.org/content/355/6329
102 http://syntheticbiology.org/BioBricks.html
103 http://science.sciencemag.org/content/353/6297/aad8559
104 http://pubs.acs.org/doi/abs/10.1021/sb400077j
105 https://www.nature.com/nbt/journal/v35/n5/full/nbt.3805.html
106 http://www.cell.com/trends/plant-science/abstract/S1360-1385(15)00049-7
107 http://pubs.acs.org/doi/abs/10.1021/acssynbio.5b00252
108 http://www.cell.com/fulltext/S0092-8674%2816%2930505-0
109 https://www.nature.com/news/synthetic-biology-firms-shift-focus-1.14602
110 https://www.cbinsights.com/research/synthetic-biology-top-sectors/

yeast to produce a precursor to malaria drug artemisinin.[111] According to CBI Insights, start-ups developing next-generation pharmaceuticals are attracting the most investment[112] and there are already some products in clinical trials.[113]

The field still faces considerable challenges. Stagnant oil prices have undercut demand for new ways of producing fuels and petroleum-based chemicals, while foods and fragrances need to overcome consumer aversion to “synthetic” products and pharmaceuticals need to clear considerable regulatory hurdles.[114] Despite rapidly falling costs, DNA synthesis still costs roughly 10 cents per base pair. Building the comparatively simple synthetic yeast genome cost $1.25m not including materials, labor and infrastructure.[115] On the technical front, analogies to electrical components can be misleading as our understanding of the complex interplay of processes in living organisms is still rudimentary. Furthermore, natural evolution still happens in colonies of synthetic microorganisms, and can wreak havoc with the most careful bioengineered designs. This means interventions can have unexpected outcomes and the field is just as much about trial-and-error as forward engineering.[116] There have been increasing calls to move beyond the mainstay organisms E. coli and yeast as they are often incompatible with downstream biotech processes[117] and not robust enough for real-world applications.[118] The field also has problems with reproducibility due to the lack of standards though there has been a significant push from both academia and industry to deal with this issue.[119] At the same time, increasing use of automation, particularly at synthetic biology “foundries” like Gingko Bioworks, is helping to overcome complexity by making it possible to rapidly iterate through potential biomolecular designs.[120]



Source: Chemistry World

The most transformative applications of synthetic biology in the near term are likely to be in medicine. Asides from the potential to optimize current drug manufacturing processes, the approach could yield entirely new treatments. SynLogic, backed by the Bill & Melinda Gates foundation, is reengineering the bacteria found in the human gut to fight disease.[121] eGensis is using CRISPR gene-editing technology to make it feasible to use pig organs for human transplants[122] and Editas Medicine wants to use CRISPR to directly edit people’s genomes to treat genetic disease.[123] In the next few decades it’s not inconceivable that our bodies will be patrolled by genetically engineered microbes that can both detect and treat disease automatically, while genetic defects will be as treatable as the flu.

With increasing concerns over global food security, agriculture could be another area where synthetic biology will have a major impact. German chemical giant Bayer and Ginkgo Bioworks are working to re-engineer the symbiotic microbes that allow legume vegetables to create their own fertilizer so they can colonize any plant.[124] Synthetic gene

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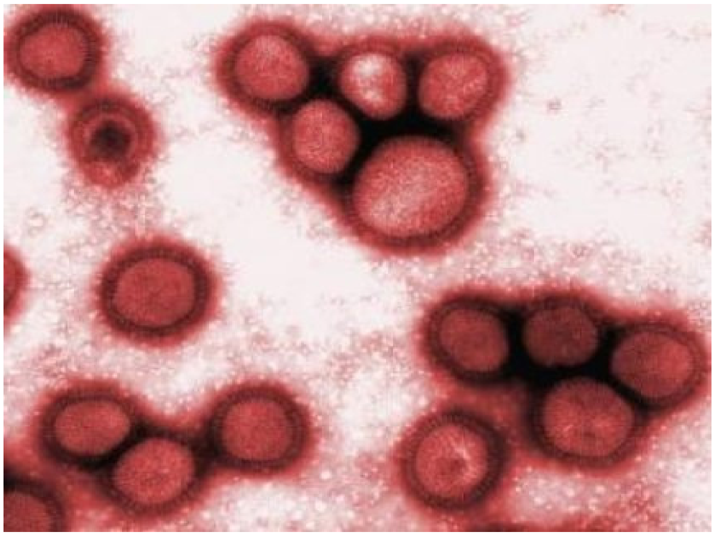
[111] http://annualreport.dsm.com/ar2016/en_US/7-3-innovation-center.html#H4794108691
[112] http://www.reuters.com/article/health-malaria-sanofi/sanofi-rolls-out-large-scale-supply-of-synthetic-malaria-drug-idUSL6N0QI1B020140812
[113] http://www.sciencemag.org/custom-publishing/technology-features/synthetic-biology-s-clinical-applications
[114] https://phys.org/news/2015-09-introduction-start-ups-synthetic-biology.html
[115] http://science.sciencemag.org/content/355/6329/1040.full
[116] https://eandt.theiet.org/content/articles/2016/07/engineering-the-stuff-of-life/
[117] https://www.nature.com/nrmicro/journal/v12/n5/full/nrmicro3261.html
[118] http://pubs.acs.org/doi/abs/10.1021/acssynbio.6b00256
[119] http://www.nature.com/news/synthetic-biologists-seek-standards-for-nascent-field-1.17271
[120] https://spectrum.ieee.org/biomedical/devices/the-robot-revolution-comes-to-synthetic-biology
[121] https://www.synlogictx.com/synthetic-biotics/precision-programming-of-the-microbiome/
[122] https://www.egenesisbio.com/
[123] http://www.editasmedicine.com/
[124] https://www.wired.com/story/with-designer-bacteria-crops-could-one-day-fertilize-themselves/

drives, chunks of DNA designed to increase the chance of particular genes being inherited, are already being tested as a means of eradicating pests, though evolution may help Nature find a way around this tactic.[125] An Israeli team has even shown it could be possible to reengineer photosynthesis to make crop plants more efficient.[126] Advances in agriculture are also linked to future synthetic biofuels, which tend to use organic material as feedstock. So far the economics don't make sense, but dwindling supplies of oil could mean that changes in the coming decades. Concerns around climate change though may mean carbon-based fuels become increasingly unpopular and improvements in battery technology could render them obsolete over the same timescale.[127]

Dramatic increases in defense funding for the field hint at the technology's military promise – Defense Advanced Research Projects Agency (DARPA) funding went from $0 in 2010 to more than $100m in 2014.[128] Some projects are obviously defense-related such as efforts to use synthetic microbes to produce explosives free of heavy metals[129] or improved boron carbide armor.[130] There are also efforts to integrate engineered microbes into electronics to power them via photosynthesis, act as advanced biosensors or even make soldiers stronger, faster and able to heal themselves.[131] NASA also thinks that synthetic microorganisms will be essential for future deep space missions to provide astronauts with nutrients or feedstock to produce structural materials on distant planets.[132]

DARPA is also funding research in areas less obviously linked to defense. Its Safe Genes program aims to develop gene drives, but also countermeasures to fight against them well and "genetic remediation" tools to reverse their effects.[133] The Insect Allies program is looking to use insects to deliver genes to crops designed protect against natural or engineered pathogens that could disrupt food supplies.[134] These programs point to the "dual-use" nature of many synthetic biology technologies, which could be exploited by future adversaries.

The possibility of rogue states or terror groups using synthetic biology to produce potent bioweapons is one of the principle risks synthetic biology poses. A consortium of national academies of science concluded in 2015 that the barriers to entry to acquiring biological weapons have been significantly eroded by recent scientific advances, though they said developing them would still require the resources of a nation state.[135] The Pentagon has funded a review by the National Academies of Sciences into the biodefense vulnerabilities created by synthetic biology due to be released next year that could include recommendations such as limits



In 2005, scientists from the Centers for Disease Control and Prevention reconstructed the virus that caused the 1918 flu pandemic, which killed between 20 and 40 million people. Publication of this research was controversial, with some experts raising concerns about the dissemination of information that could be used to engineer bioweapons. Source: https://www.sciencedaily.com/releases/2005/10/051005230557.htm

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[125] https://www.economist.com/news/science-and-technology/21725282-resistance-inevitable-promising-means-pest-control-meets-some-evolutionary

[126] http://www.pnas.org/content/107/19/8889.long

[127] https://motherboard.vice.com/en_us/article/9kway5/were-a-cheap-battery-away-from-phasing-out-fossil-fuels

[128] https://www.wilsoncenter.org/sites/default/files/final_web_print_sept2015_0.pdf

[129] http://www.slate.com/articles/technology/future_tense/2012/01/synthetic_biology_environmentally_friendly_weapons_and_the_biological_and_toxin_weapons_convention_.html

[130] https://www.gov.uk/government/news/developing-novel-materials-with-synthetic-biology

[131] https://arstechnica.com/science/2016/12/the-armys-looking-into-putting-bacteria-into-its-electronics/

[132] https://www.nasa.gov/content/synthetic-biology

[133] https://www.darpa.mil/program/safe-genes

[134] https://www.darpa.mil/news-events/2016-10-19

[135] https://royalsociety.org/topics-policy/projects/biological-toxin-weapons-convention/

on risky research and ramping up surveillance capabilities.[136] While not strictly a defense issue, synthetic biology may also pose a challenge to the "War on Drugs". Researchers recently reported taking the first steps towards reengineering yeast to produce opiates.[137] They say that within a few years strains that can carry out all the stages of opioid production could be available, potentially opening the door to people home-brewing heroin.

The greatest danger may not come from deliberate use of synthetic organisms to cause harm. Our understanding of ecosystems is still rudimentary, making it hard to predict how synthetic organisms that escape into the environment or are released in good faith will behave. Organisms with enhanced capabilities could out-compete natural species or crops while those designed for tasks like cleaning up toxins could behave in unpredictable ways or mutate beyond their intended purpose.[138] Researchers have proposed genetic "kill switches"[139] or ensuring microbes require a diet that can only be provided in a lab.[140] But as a report from Friends of the Earth notes, evolution has a tendency to work around these kinds of limitations.[141] The report also notes a more conservative concern that demand for water, fertilizer and agricultural feedstock for the synthetic production of things like fuel and plastics could put even more strain on overstretched natural resources.

A final and more philosophical risk comes from a proposal to synthesize a human genome from scratch. The HGP-write project plans to raise $100m to synthesize a human genome in a lab dish, from scratch, within 10 years.[142] The project is ostensibly aimed at boosting DNA synthesis technology, but experts have pointed out that it would almost certainly open the door to reengineering human genomes.[143] Whether the idea of designer babies is a risk or an opportunity depends on perspective, but it is likely to have dramatic legal, regulatory and ethical ramifications.

Source: Wired

Space Technology

Sixty years after Sputnik became the first artificial satellite in Earth orbit, space remains a largely under-utilized frontier. However, recent progress in low-cost commercial space flight, miniaturization, materials, and space propulsion suggest that space will be an important focus of technological innovation over the next 30 years. Much of the progress in the past five years has come from the rapidly expanding commercial space industry. SpaceX, the poster child for the emerging private space economy, has demonstrated a reusable version of its Falcon 9 rocket that can return to Earth after launch.[144] This technology would significantly reduce the cost of orbital launches. In addition, the Google Lunar XPrize offers up to $20 million to the first privately-funded team to land a spacecraft on the surface of the moon, move it 500 meters across the lunar surface, and beam high-definition video and images back to Earth. Five teams from Israel, the United States, India, Japan, and an international consortium have advanced in the competition and have approvals to launch payloads into space this year.

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[136] https://www.wired.com/story/the-pentagon-ponders-the-threat-of-synthetic-bioweapons/
[137] https://www.wired.com/2015/05/genetically-modified-yeast-will-make-possible-home-brew-opiates/
[138] http://blogs.ei.columbia.edu/2011/07/08/synthetic-biology-creating-new-forms-of-life/
[139] https://www.nature.com/nchembio/journal/v12/n2/full/nchembio.1979.html
[140] https://www.nature.com/news/gm-microbes-created-that-can-t-escape-the-lab-1.16758
[141] https://1bps6437gg8c169i0y1drtgz-wpengine.netdna-ssl.com/wp-content/uploads/wpallimport/files/archive/SynBio-Biofuels_Report_Web.pdf
[142] http://science.sciencemag.org/content/early/2016/06/01/science.aaf6850
[143] https://www.technologyreview.com/s/601610/plan-to-fabricate-a-genome-raises-questions-on-designer-humans/
[144] https://techcrunch.com/2017/03/30/spacexs-reused-falcon-9-rocket-nails-the-landing-for-a-second-time/

Internationally, government investment in space is also growing. While the U.S. still spends more on space than the rest of the world combined, $40 billion in 2013, other nations are developing their own space programs. China currently spends approximately $10.8 billion per year on space research and development, and is growing its investments in this area as it expands its broader domestic R&D agenda. Even countries as small as Slovenia, a nation of just over 2 million people with a GDP lower than every U.S. state besides Wyoming and Vermont, are investing in space technology.

Asteroid mining is a more speculative, but potentially transformative, emerging technology. There are an estimated 15,000 near-Earth asteroids[145] that could feasibly be mined with current or near-term space technologies. Just one of these, 162173 Ryugu, holds an estimated $83 billion in nickel, iron, cobalt, and other valuable elements.[146] There are significant technical barriers to making asteroid mining cost-effective. For example, it is difficult to accurately identify the composition of most asteroids using current ground and orbital sensors, and the cost of retrieving minerals from an asteroid make this uncertainty deeply unattractive to many investors. However, private investment in space technology is growing rapidly – venture capital investment in the sector was $1.8 billion in 2015, double the amount made in the previous 15 years combined.[147] The falling cost of commercial space launches, coupled with greater government investment in space technology by China and other nations, could make asteroid mining viable by 2047.


Swiss company Climeworks has developed the first commercial carbon capture plant. The facility scrubs carbon dioxide from the air and converts it to fertilizer. Source: www.climeworks.com

While the exploration—and potential colonization—of space has long captured our imaginations, a growing dependence on space-based infrastructure could lead to new frictions here on Earth. As more nations come to rely on space-based assets the control of space could become a significant flash point. The militarization of space is not out of the question, and anti-satellite warfare could have profound effects on the U.S. Army, which relies heavily on satellites for secure global communications, intelligence gathering, and coordinating joint maneuver.

Climate Change Adaptation Technology

Adapting to a warming planet and ensuring security on it will require action on both the root causes of climate change and its effects. Progress on both fronts has been slow to date. Switching to lower-carbon energy sources and deploying efficiency measures have helped stabilize CO_2 emissions over the past three years.[148] However, the Earth continues to warm and the effects of climate change are being felt more acutely.

More drastic measures, including forms of geoengineering, are still somewhat taboo but have slowly begun to crop up in mainstream discussion. Two major categories of geoengineering are carbon capture and sequestration (CCS) and solar radiation management (SRM, i.e. reflecting sunlight to cool the earth). Direct carbon capture from the air is technically feasible today. Scrubbing CO_2 from power plant flue gas and storing it in geologic structures costs $40-140 per ton of CO_2, depending on the type of plant. The technology becomes much more cost effective if the CO_2 can be sold for enhanced oil recovery or other uses.[149] To

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[145] https://www.nasa.gov/feature/jpl/catalog-of-known-near-earth-asteroids-tops-15000

[146] This estimate comes from Astrarank (http://www.asterank.com/), which uses data on the spectral composition of near-Earth asteroids to estimate their market value.

[147] http://fortune.com/2016/02/22/vcs-invested-more-in-space-startups-last-year/

[148] https://www.iea.org/newsroom/news/2017/march/iea-finds-co2-emissions-flat-for-third-straight-year-even-as-global-economy-grew.html

[149] Rubin, ES et al. The cost of CO2 capture and storage. Int J Greenhouse Gas Control (2015). https://doi.org/10.1016/j.ijggc.2015.05.018

this end, XPRIZE is sponsoring a $20 million competition for technologies that use CO_2 in valuable products[150] that could range from athletic shoes to office furniture to diesel fuel.[151] SRM in the form of spraying sulfate aerosols into the stratosphere is relatively simple technologically, but its risks remain poorly understood.

Coastal regions are particularly important potential beneficiaries of climate change technology. Sea level rise, large storm surges, and land subsidence in urban areas put coastal populations at risk. Adaptation approaches include hardening shorelines with seawalls, bulkheads, and other structures to preserve existing development. There are also "softer" approaches, such as restoring sediment flow to replenish beaches and planting seagrass to restore ecosystems and reduce erosion[152]. Some more innovative projects include: creating new topography on New York's Governors Island, essentially lifting the island out of the flood zone,[153] and a proposed ring of "green" infrastructure around Lower Manhattan that would serve as parkland in fair weather and wetland storm buffers in foul. The U.S. Department of Housing and Urban Development provided $335 million to build 2 miles of this barrier.[154]

Ramping up climate adaptation technologies is increasingly urgent. In its 2013 report, the IPCC recognizes that geoengineering may be necessary to limit warming to 2°C; some climate models indicate that negative emissions may be required.[155] Scientists have argued for CO_2 capture from ambient air to help meet this target by addressing emissions from other, dispersed sources such as planes and automobiles.[156] The Center for Negative Carbon Emissions at Arizona State University has developed a sorbent which absorbs CO_2 when dry and releases it when exposed moisture.[157] The material would be placed within physical structures, creating "artificial trees" that remove CO_2 from air flowing through. Carbon capture can improve with sorbents that use less energy to release the carbon dioxide and technologies that move air over solvents faster without costing energy. The Virgin Earth Challenge is offering $25 million in prize money to drive innovation in scalable atmospheric CO_2 removal technology.


Source: http://www.indiawaterportal.org

On the SRM side, research into the technology's effects is still primarily in the modeling stage. However, Harvard's David Keith, a leading expert in the field, is on track for a pioneering small-scale experiment injecting reflective particles into the atmosphere.[158] Partnering with World View Enterprises, a high-altitude balloon would spray a small amount of particles into the atmosphere, while an attached gondola housing sensors would monitor the effects. The plans include testing different materials (e.g. sulfur dioxide, alumina, calcium carbonate), and measuring their reflectivity and reaction with other atmospheric compounds. Keith first proposed the experiment in a 2014 paper and said at a recent forum that he hopes to begin testing in early 2018. He has funding from Bill Gates, the Alfred P. Sloan Foundation, and other philanthropists.

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[150] https://carbon.xprize.org/
[151] http://www.anthropocenemagazine.org/2016/10/carbon-negative-furniture/
[152] U.S. EPA (2009). Synthesis of Adaptation Options for Coastal Areas.Washington, DC, U.S. Environmental Protection Agency, Climate Ready Estuaries Program. EPA 430-F-08-024, January 2009.
[153] http://west8.com/projects/all/governors_island_phase_2_the_hills/
[154] https://www.asla.org/2016awards/172453.html
[155] https://www.scientificamerican.com/article/latest-ipcc-climate-report-puts-geoengineering-in-the-spotlight/
[156] Lackner, KS et al. "The urgency of the development of CO2 capture from ambient air." PNAS 2012.
[157] https://cnce.engineering.asu.edu/research/
[158] https://www.technologyreview.com/s/603974/harvard-scientists-moving-ahead-on-plans-for-atmospheric-geoengineering-experiments/

On the ground, where sea levels are rising and storms intensifying, a recent projection shows that—on the conservative end—880 million people around the world will live in low elevation coastal zones by 2030, and that number could exceed one billion by 2060.[159] A report from the American Security Project recommends U.S. federal programs to shift their focus from recovery to prevention efforts and to "explore alternative methods such as nature-based approaches to counter sea level rise."[160] The Nature Conservancy along with reinsurance company Swiss Re found that wetland and oyster reef restoration are among the most cost-effective coastal flood mitigation measures. They calculated that in the Gulf of Mexico alone, nature-based coastal defenses could help avert $50 billion in damages over a 20-year period.[161] In the future, real-time sensors and responsive robotics may be able to control hydrologic environments and assist in rebuilding natural coastal defenses.[162]

The American Security Project calls climate change an "accelerant of instability" or a "threat multiplier." Using technologies that help us mitigate or become resilient in the face of climate change can lessen the severity and effects of natural disasters. Severe storms and flooding events can overwhelm local resources and require military resources be used toward humanitarian aid.[163] Climate change adaptation may help reduce the demand for such aid.

Yet geoengineering, particularly SRM, presents potentially serious risks and the possibility for inciting conflict. Models suggest that significant cooling can be achieved with few major technological advances. This means that a single nation or rogue actor may be able to intervene in climatic forces on its own. Yet we do not know how SRM will affect natural processes and human livelihoods. Further, the consequences will likely be felt in different ways in different regions. The National Academy of Sciences report on climate intervention recommends national or international coordination for any such measures, accompanied by observing systems that can quantify their effects.[164]

Reengineering coastlines comes with difficult tradeoffs, particularly in developed and economically important areas. Halting channel dredging so that sediment may naturally replenish coastlines may disrupt shipping and commerce. Hard infrastructure such as seawalls and floodgates may protect the land behind them, only to divert water toward more-exposed shoreline. And poorly maintained structures may prove unable to withstand stronger storms and rising sea levels.

Risks, Opportunities, and Technological Leadership in 2047

A total of 869 subject matter experts from across the Army S&T enterprise were surveyed on the relative degree of risk and opportunity associated with the trends discussed above. In this context, opportunity and risk were defined as the emergence of new technology-enabled capabilities that could provide a tactical edge to the U.S. and/or potential adversaries within the next 30 years, affecting the Army's relative strength. In addition, the SMEs were asked to assess the likely technological position of the United States relative to global competitors in 2047. The survey results shed additional light on how these technologies might impact Army capabilities in the deep future.

There was a strong correlation between risk and opportunity, as shown in Figure 1.[165] Technologies rated by Army SMEs as holding greater opportunity, such as robotics and artificial intelligence, were also deemed to carry the most risk. Conversely, technologies related to climate change and space were viewed as relatively low-opportunity and low-risk compared with the other trends. Although the survey did not ask respondents to discuss the factors that motivated their ratings, these results are consistent with global trends towards the diffusion of innovation and the rise of near-peer

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[159] http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0118571#sec007
[160] "Resilience in the Face of Rising Seas: Regional Approaches to Sea Level Rise." American Security Project, September 2016.
[161] Economics of Coastal Adaptation. The Nature Conservancy, April 2016.
[162] http://www.gsd.harvard.edu/exhibition/responsive-topography-fluvial-landscapes/
[163] Future Operating Environment 2035. UK Ministry of Defence, November 2014.
[164] "Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration." National Academy of Sciences, 2015
[165] For readers interested in the statistics, the correlation between normalized risk and opportunity scores was 0.87.

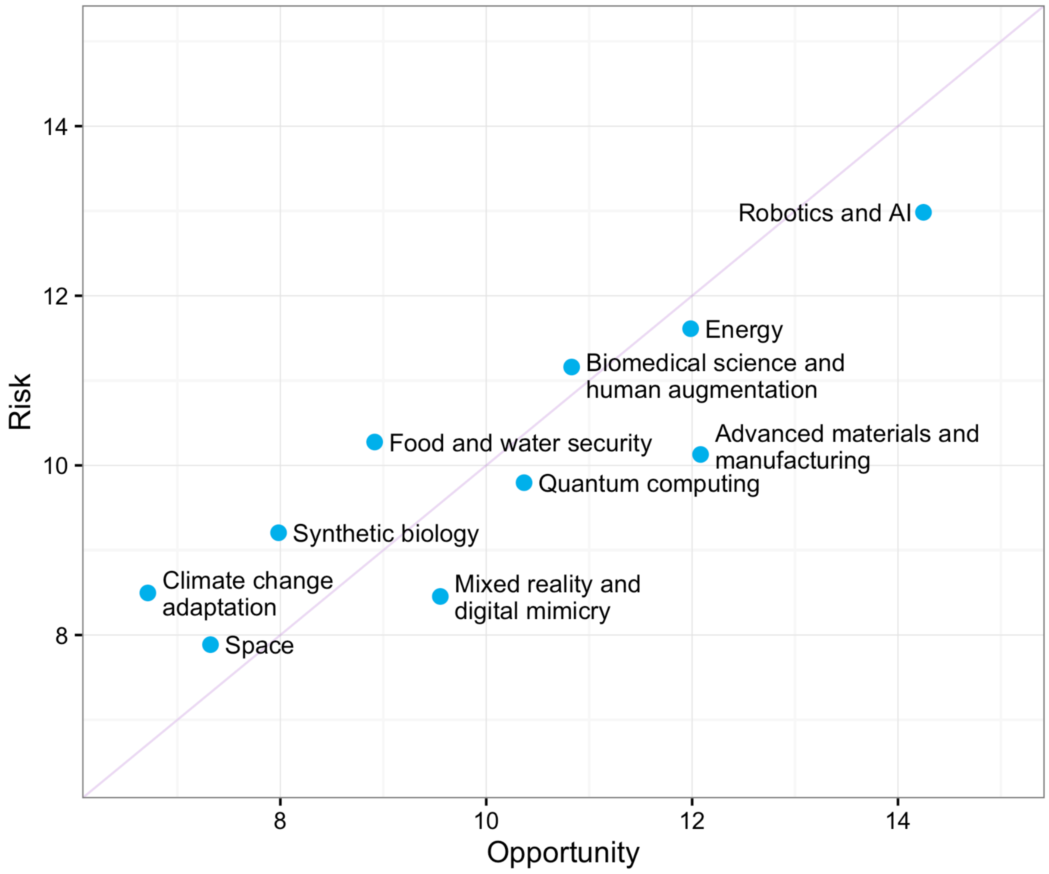

Figure 1. A plot of average risk vs. opportunity scores based on responses from the SME survey. The red diagonal line marks isometric risk and opportunity scores.

competitors to the United States' traditional dominance in advanced technology. For example, under its "Made in China 2025" plan, China is making investments to automate many manufacturing sectors, including electronics, home appliances, logistics, and food production. In addition, China is focused on developing a home-grown robotics industry. The country plans to internally design and produce half of the robots used in their economy by 2020.[166]

The risk-opportunity ratio also differed across trends. As Figure 1 shows, SMEs rated five of the trends as presenting relative greater opportunity compared with their degree of risk (the red line in Figure 1 indicates equal risk and opportunity ratings). These technologies were: robotics and AI; energy; advanced materials and manufacturing; quantum computing; and mixed reality digital mimicry. In contrast, biomedical science and human augmentation; food and water security; synthetic biology; climate change adaptation; and space technologies were rated as presenting relative greater risk relative to potential opportunity for the Army.

What might these results suggest? One possibility is that technologies rated as presenting greater opportunity than risk might be domains in which SMEs felt confident in sustained U.S. technological superiority. Technological advantage might enable the U.S. to take maximum advantage of emerging opportunities while mitigating future risks. This is consistent with data shown in Figure 2, which presents SME ratings of the likelihood that the U.S. will possess a technological lead over other nations in 2047. Apart from energy, the technologies rated as having relative greater opportunity than risk were also the most likely domains for sustained technological advantage. Likewise, apart from

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[166] https://www.bloomberg.com/news/articles/2017-04-24/resistance-is-futile-china-s-conquest-plan-for-robot-industry

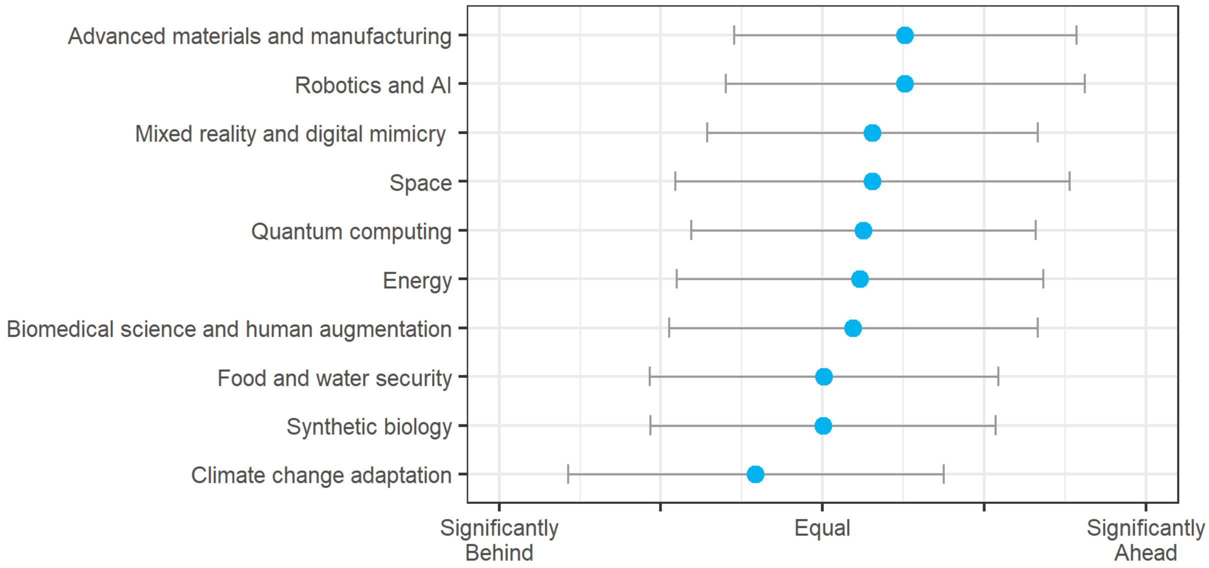

Figure 2. Average ratings of likely U.S. technological position compared with the rest of the world in 2047. The error bars represent the 95% confidence interval around each mean. Statistically, one would expect the "true" value population mean (i.e., the value that would be obtained if all Army SMEs had responded) to fall within the range defined by the confidence interval.

space, the technologies carrying greater risk relative to opportunity were those for which the U.S. was more likely to be at parity or behind major competitors.

SMEs were generally optimistic about the prospects for continued U.S. technological leadership, forecasting a slight edge for the U.S. in seven of the ten trends. SMEs estimated that the U.S. would be at parity with global competitors in the areas of food and water security and synthetic biology, but would lag slightly behind the world in climate change adaptation. However, there was a relatively high degree of variability in SME responses, and the data suggested that broad loss of U.S. technological dominance cannot be discounted. Again, the intent of this survey was to provide a broad view of risk, opportunity, and leadership. Army leadership should conduct a deeper analysis of the risk of losing our technological lead in these key areas, and what steps might be taken to mitigate that risk.

Another possible explanation for the asymmetry in risk-opportunity evaluations is the dynamic that exists between new technology-enabled capabilities and national willingness to pursue those capabilities. As an example, synthetic biology presents potentially transformative applications in biofuels, self-healing materials, personalized medicine, and other domains. However, it also raises the specter of manipulating the fundamental character of life and could create significant dangers to public health from invasive synthetic organisms, bioweapons, and other threat vectors. Materials and robotics, on the other hand, also carry significant risks, but offer compelling solutions to a wide range of capability needs identified by Army leadership, including force protection, sustainment, expeditionary maneuver, and other core competencies that will be essential in the future operating environment.[167] SME ratings could reflect this tradeoff. This is speculative, given that the survey did not address motivations behind the ratings. However, it is worth considering the role that national character and other variables beyond capability payoff influence how the U.S. and potential competitors set S&T priorities.

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167 TRADOC (2014). U.S. Army Operating Concept: Win in a Complex World. TRADOC Pamphlet 525-3-1. Available from http://www.tradoc.army.mil/tpubs/pams/tp525-3-1.pdf.

Emerging trends in S&T over the next 30 years will play out against a background of ongoing sociopolitical, economic, and environmental change. Over the coming decides, six key trends are likely to shape the nexus between sociopolitical change, technology, and security:

- Urbanization
- Climate change
- Resource constraints
- Shifting demographics
- Globalization of innovation
- Rise of a global middle class

Urbanization

By 2047, approximately two-thirds of the world's population will live in urban areas.[168] The majority of this growth is likely to occur in the developing world, particularly in Asia and Africa, as economic growth and foreign investments by China and other rising economies draw more residents to job opportunities near cities. The trend towards urbanization will expand the number of megacities – cities with more than 10 million residents – from 28 in 2015 to 41 by 2030.[169] If urbanization is managed successfully, hundreds of millions of people could be raised out of poverty by strong economic growth, though the link between urbanization and economic growth depends strongly on domestic policy.[170] On the other hand, mismanaged growth could lead to cities that cannot provide enough fresh water, food, electricity, transportation access, and sanitation to sustain a healthy, productive population. Rapid migration to cities and increasing urban population densities could also exacerbate ethnic or religious tensions, particularly in cities that cannot provide sufficient resources to keep people safe and employed.

From a technology perspective, urbanization will likely encourage innovation on multiple fronts. Successful cities will need to develop innovative transportation systems that move people and good efficiently without contributing to smog and other forms of pollution. Autonomous vehicles are likely to play a key role in future transportation infrastructure, and these vehicles could be tied into city-wide traffic networks controlled by artificial intelligence algorithms. The need to provide food and fresh water to millions of urban residents will drive innovations such as vertical farming and water harvesting (e.g., graywater recycling). As cities grow, robots could be called upon to serve in a wide range of municipal services, such as augmenting police and other emergency services and performing infrastructure monitoring and maintenance.

An artist's rendering of vertical slums in an imagined, deep-future version of Lagos, Nigeria. Source: http://www.designindaba.com/articles/creative-work/artist-imagines-colossal-vertical-slums-lagos

Cities will also become central to emerging energy technologies, as rising urban populations and the continued adoption of consumer and municipal electronics drives a rapid increase in urban energy demands. Distributed renewable technologies, such as micro-turbines mounted to take advantage of the "urban wind tunnel" effect and rooftop solar could form the foundation of urban power generation. Smart grids that optimize energy mix from multiple generation sources could also make cities more energy efficient and resilient.

Climate adaptation technologies are also likely to become more important as cities grow over the next 30 years. New

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[168] United Nations, Department of Economic and Social Affairs, Population Division (2014). World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).

[169] Ibid.

[170] Chen, M., Zhang, H., Liu, W., & Zhang, W. (2014). The global pattern of urbanization and economic growth: evidence from the last three decades. PloS one, 9(8), e103799.

York and other cities are already preparing for rising sea levels by raising streets and installing flood walls and other mitigation systems. More elaborate measures are also emerging. For example, officials in French Polynesia are exploring the creation of a city of floating islands, artificial structures that would be self-sustaining and capable of rising with surrounding oceans.[171]

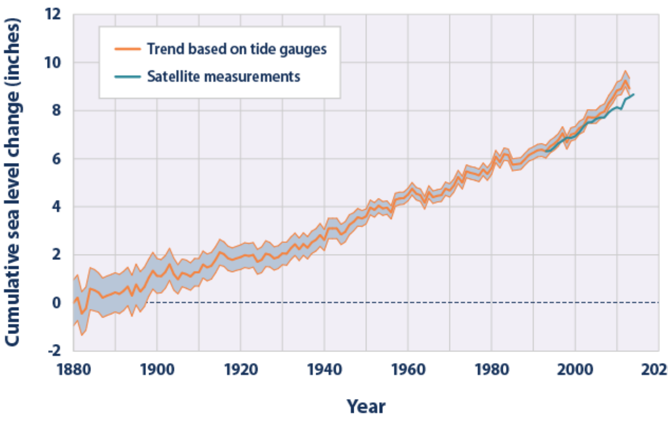
Climate Change

By 2050, the average global surface temperature is forecast to rise between 2.5 and 5.4 degrees Fahrenheit.[172]. Sea levels could rise up to 6.6 feet by the end of the century,[173] leading to increased flooding. Many coastal areas will become inundated with water, transforming coastlines around the world and adversely affecting millions of people living in coastal cities. Eight of the ten largest cities in the world currently lie on the coast, and the number of people living in coastal cities is likely to expand greatly by 2047.

Temperature change will also affect global weather patterns, leading to more frequent and more severe weather events in many parts of the world. Desertification is likely to accelerate in the absence of major national and regional policy changes, leading to a decline in agricultural output across Asia and Africa. Agriculture in equatorial regions will be particularly affected, potentially causing food shortages across North Africa and the Middle East.

Oceans absorb a large amount of atmospheric carbon dioxide, and will absorb more as ocean temperatures rise. One consequence of this is that ocean acidification will likely increase by up to 70% by 2050.[174] Acidification will cause potentially devastating ripple effects throughout the oceanic ecosystem, causing a decline in global populations of fish and other aquatic food stocks and increasing food stress in many regions of the world. At the same time, melting of polar ice will open vast new regions to exploration for energy and minerals. The Arctic is already becoming a focus of strategic maneuvering for the U.S., Russia, and Europe, and expanded access to polar resources could trigger interstate conflicts.[175]

Global Average Absolute Sea Level Change, 1880–2014



Data sources:
- CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2015 update to data originally published in: Church, J.A., and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st century. Surv. Geophys. 32:585–602. www.cmar.csiro.au/sealevel/sl_data_cmar.html.
- NOAA (National Oceanic and Atmospheric Administration). 2015. Laboratory for Satellite Altimetry: Sea level rise. Accessed June 2015. http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_timeseries_global.php.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climatechange/indicators.

Historical seal level data, indicating a clear upward trend. Source: Wikipedia (image)

Most experts agree that there we are unlikely to entirely avoid the negative effects of climate change. Therefore, science and technology will likely play a key role in mitigating the impacts of climate change. For example, artificial intelligence could be used to predict flooding hazards based on near-term meteorological data and long-term climate modeling. This would enable proactive responses by government planners and emergency services. Agricultural technologies such as vertical farming could enable cities to meet food demand locally through farming methods that are more resilient to drought and other climate influences. Technologies such as cultured meat – meat

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[171] https://www.technologyreview.com/s/603527/new-york-city-is-building-for-a-future-of-flooding/

[172] IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32. Available from http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf.

[173] https://sealevel.nasa.gov/understanding-sea-level/projections/empirical-projections

[174] Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., ... & Key, R. M. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437(7059), 681-686.

[175] UK Ministry of Defense (2015). Future Operating Environment 2035. Available from https://www.gov.uk/government/publications/future-operating-environment-2035.

made from cells grown in a laboratory[176] - could provide an alternative to resource-intensive livestock farming and create a sustainable supply of protein for growing populations.

Resource Constraints

Over the next 30 years, global demand for food, water, energy, and material resources is likely to continue to increase dramatically. Global fresh water demand is projected to grow by 55% by 2045,[177] and unless steps are taken to mitigate water shortages, around 3.9 billion people – over 40% of the world's population – could experience water stress. It is likely that food and energy resources will come under pressure from population growth. For instance, estimates indicate that up to 25% of farmland is already degraded due to overuse of chemical fertilizers and poor crop management practices.[178] Left unchecked, this trend could lead to declines in agricultural output, increasing the risk of famine. Similarly, global energy demand is expected to double by 2047, and energy supply is projected to undershoot demand,[179] despite increased investment in renewables and fossil fuel exploration.

Global reserves of materials such as copper and lithium are declining as demand for these finite resources increases. Experts predict that 83 billion tons of minerals, metals and biomass will be extracted from the earth in the year 2030: 55 percent more than in 2010.[180] Countries that control large resource reserves are likely to gain immense control over the global economy. For example, China currently supplies 97% of global demand for rare earth metals. The Chinese government has already tightened rare earth exports, driving up prices for electronic components and boosting its own domestic electronics industry. In response to Chinese cutbacks, Japan has been actively pursuing other sources of rare eart, funding mine exploration projects in India, Australia, and Kazakhstan, along with riskier ventures such as deep-sea mining in the Pacific ocean[181].

Miners dig an open-earth copper mine in eastern Congo. Source: Reuters

Resource constraints will be a powerful driver of global research and technology development. Water harvesting and recycling technologies, such as desalination and water vapor farming, could reduce water stress. Agricultural output will likely benefit from new advances in transgenic crops, micro-irrigation, and autonomous systems for crop management. New manufacturing methods such as 3D and 4D printing will likely reduce demand for new resource production by expanding the use of recycled materials, particularly for the manufacture of consumer goods.

Shifting Demographics

The global population is on pace to reach 9.5 billion by 2045[182] - a 28% increase over the current world population of 7.4 billion. Many factors are contributing to population growth, including a decline in deaths from infectious diseases due to public health initiatives, rising birth rates and declining infant mortality in the developing world, improved sanitation, and enhanced access to medical care. Developing nations are likely to account for around 97% of this growth, with Africa alone accounting for 49% of global population growth by 2050. The human population is also

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[176] http://www.sciencemag.org/news/2017/03/artificial-chicken-grown-cells-gets-taste-test-who-will-regulate-it

[177] OECD (2012). Environmental Outlook to 2050. Available from http://www.oecd.org/env/indicators-modelling-outlooks/oecdenvironmentaloutlookto2050theconsequencesofinaction.htm.

[178] Godfray, H. C. J. (2014). The challenge of feeding 9–10 billion people equitably and sustainably. The Journal of Agricultural Science, 152(S1), 2-8.

[179] International Energy Agency (2016). World Energy Outlook. Available from http://www.worldenergyoutlook.org/.

[180] KPMG International, De Boer, Y., & van Bergen, B. (2012). Expect the unexpected: Building business value in a changing world. KPMG International.

[181] https://www.reuters.com/article/us-japan-rareearths/japan-loosens-chinas-grip-on-rare-earths-supplies-idUSKBN0H001T20140905

[182] United Nations (2015). World Population Prospects. Available from http://esa.un.org/unpd/wpp/.

aging – over the next 30 years the median global age will increase from 29.6 to 36.1, with 1.4 billion people over the age of 65. Europe, Japan, and the United States are at the leading edge of this “age bubble”. Most experts forecast that climate change, civil unrest caused by political and economic tensions, and the shifting global economic landscape will also drive an increase in migration over the next 30 years. While migratory flows from the developing to the developed world will continue, we may see increased migration between developing nations themselves as economies in Africa and Asia continue expanding.

Technology will both reinforce and respond to these demographic changes. Advances in biomedical science will contribute to a reduction in deaths due to disease, genetic conditions, and lifestyle-related illness. Medical advances will also reduce child and mother mortality, especially in the developing world. Augmentation technologies will likely increase the number of senior citizens who remain productive well into their 70’s and 80s. At the same time, an overall increase in the population will likely fuel a growing market for AI-powered health care analytics and robots designed to assist the elderly.

Mixed reality technologies could allow immigrants to virtually visit their homelands and maintain contact with their own cultures reducing the stress of emigration while creating potential challenges for assimilation. Migration could also encourage governments to develop new applications for analytics to track migratory flows – which could have unintended consequences if used for racial or ethnic profiling.

Globalization of Innovation

Globalization has been underway for the past 30 years, and shows little sign of slowing down. On balance, globalization has expanded economic opportunity across many parts of the developing world and contributed to a broad increase in standard of living. However, globalization has also increased environmental degradation, generated significant disruption in labor markets across the developed world, and led to worker exploitation in many developing countries. Tensions caused by globalization and immigration are fueling populist backlash in many nations, which could lead to protectionist policies that slow globalization in the near term. However, the economic appeal of integrated global markets, and rise of new economic players such as China and India makes it unlikely that isolationist economics will be successful in 2047.

Innovation is likely to diffuse over the next 30 years, as emerging powers invest in home-grown industries. For example, from 2012 through 2016, Chinese R&D investment grew from 1.6% of GDP in 2010 to 1.96% in 2016.[183] In contrast, U.S. R&D expenditures have remained constant at around 2.8% of GDP over the same period. From 2016 to 2017, the U.S. increased R&D spending across all sectors by 2.9%, to $527.5 billion. China, on the other hand, increased R&D by 7.1%, to $429.5 billion.[184] Based on forecasts of GDP growth China could surpass the U.S. in R&D investment by the year 2026. China already invests more in R&D than all of Europe combined.

China is making major investments in the solar power industry. It leads the world in solar energy production with a generation capacity of 101.82 gigawatts per year, and added 24.4 gigawatts in the first six months of 2017 alone. Sources: McKinsey (image), https://www.nextbigfuture.com/2017/07/china-producing-60-gigawatts-of-solar-panels-this-year-up-25.html.

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[183] Statistic based on data from the Industrial Research Institute’s annual Global R&D Funding Forecast.
[184] Industrial Research Institute 2017 Global R&D Funding Forecast.

From a technology standpoint, the globalization of innovation will mean that the United States' influence over the global research and development agenda will likely decline relative to other countries, especially China. We are already seeing early signals of this shift: China filed 1.01 million patent applications in 2015, almost double the number files by U.S.-based innovators.[185] The Chinese National Patent Development Strategy prioritizes seven industries: biotechnology, alternative energy, clean energy vehicles, energy conservation, high-end equipment manufacturing, broadband infrastructure, and high-end semiconductors. Given the massive investments China is making in research and development, it is likely that we will see a spike in innovation in these areas, particularly in areas where Chinese and U.S. investments overlap, such as biotechnology. In the case of energy technologies, China could become the global leader, out-innovating the United States in this critical technology sector.

Rise of a Global Middle Class

Membership in the global middle class is expected to more than double over the next 15 years, from 1.8 billion to almost 5 billion. By 2030, 60% of the world's population could belong to the middle class, with the most growth occurring in Asia.[186] The growth of the global middle class will likely be accompanied by a significant worldwide increase in education level and access to technology. By 2030, around 90% of the world's population will know how to read, and 50% will have Internet access.[187]

As incomes rise, people around the world will have more disposable income to spend on consumer electronics and other goods and services. This could fuel significant technology adoption across the developing world, opening new markets for innovators and putting a global face on technology design. For example, a demand for mass-market autonomous vehicles could drive innovation in battery technology and materials to drive costs down. Demand for human augmentation technologies could also grow, especially for less expensive augmentations such as wearables and pharmaceutical enhancements. Blended reality technologies may become more ubiquitous as delivery vehicles for immersive, interactive entertainment and distributed education. Investments in consumer artificial intelligence may grow as the emerging middle class invests in smart home products and governments make investments in digitally-enhanced infrastructure. While the rate of growth in these and other technology sectors will depend on factors besides economic incentives, it is likely that the rise of the global middle class will fuel broad-based innovation in science and technology.

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[185] http://www.wipo.int/pressroom/en/articles/2016/article_0017.html

[186] European Strategy and Policy Analysis System (2015). Global trends to 2030: Can the EU meet the challenges ahead? Available from http://europa.eu/espas/pdf/espas-report-2015.pdf.

[187] Ibid.

CONCLUSION

This edition of the S&T Emerging Trends report synthesizes 52 open-source forecasts of science and technology trends that are likely to influence the U.S. Army within the next 30 years. The objective was to establish a consolidated look at S&T domains that are most likely to generate revolutionary or disruptive change of interest to the Army over the next 30 years. By identifying common themes across multiple trend analyses this report aims to provide a ready reference for Army leadership as it considers the role S&T will play in shaping the future of Army operations. A total of 947 S&T trends were identified in the source documents. Statistical topic modeling produced a refined set of 10 overarching trends:

- Robotics, artificial intelligence, and automation
- Advanced materials and manufacturing
- Energy production, harvesting, storage, and distribution
- Biomedical science and human augmentation
- Quantum computing
- Mixed reality and digital mimicry
- Food and water security technologies
- Synthetic biology
- Space technologies
- Climate change adaptation technologies

What kind of a world can we envision based on how these trends are likely to evolve? It seems highly likely that, by 2047, robotics and artificial intelligence will be ubiquitous and deeply integrated into the global economy, civil society, and defense. Much has been written about the potentially destabilizing effects of replacing human workers with robots. The question is whether this disruption, which is likely to accelerate over the next 10 years, will have reached a new, stable status quo by 2047. It is possible that the global economic and political order may figure out how to deal with the displacement of human workers that will almost certainly be caused by robotics and AI. The Industrial Revolution provides one example of such a best-case scenario. On the other hand, it is important to consider the implications for U.S. national security and Army operations if this rapprochement between human and machine fails to materialize.

Developments in materials science and additive manufacturing could lead to a future of highly efficient renewable energy, batteries that power cars and balance smart power grids, lighter-weight armored vehicles that are more efficient yet better-protected than current systems, and a host of other valuable applications. Additive manufacturing could give forward-deployed Army units the ability to produce repair parts, medical supplies, and even food on an on-demand basis. Synthetic biology could create breakthrough capabilities in biofuels, energy harvesting, and functional materials. However, complex nanomaterials and synthetic biology could also create new sources of environmental contamination, and 3D printing could give adversaries the ability to manufacture weapons from digital designs shared freely on dark networks.

Biomedical advances and developments in human augmentation could improve public health across the world. In general, one would expect healthier populations to be more stable and prosperous. However, lack of access to advanced medical interventions could create friction in the developing world and provide a new rallying cry for terrorists and other violent non-state actors. Augmentation could solve the long-standing challenges of Soldier load. Furthermore, augmentation could help offset declines in physical strength and endurance associated with normal aging. Coupled with medical innovations that extend a person's "health-span", the Army could have officers and NCOs with decades of hard-earned experience able to sustain the peak physical performance of youth.

The future of information technology could be transformed by quantum computing. Quantum encryption, for example, could greatly improve cyber-defense and lead to more secure communications. However, the broad potential of quantum computing across commercial and defense applications makes this technology a prime candidate for a global technological arms race. Countries like China are already investing in this area, and are demonstrating rapid advances that will likely challenge U.S. dominance over the coming decades. Quantum computing has been “just over the horizon” for many years, but current signals suggest that real-world applications are within reach. Does the Army have a thoughtful strategy for quantum, and does that strategy account for scenarios in which China and other nations possess equivalent or superior quantum computing capabilities?

Likewise, virtual and augmented reality technologies are evolving rapidly. It seems likely that augmented and mixed reality will be widely available in consumer devices and military hardware by 2047. One potentially risky development is the confluence of computer-generated imagery, voice synthesis, and artificial intelligence. It is possible that, by 2047, avatars will be capable of mimicking political leaders, military commanders, and other important personnel. How will the Army handle identify verification and protection in an era of digital mimics?

Finally, while there is disagreement about the ultimate magnitude of climate change, the data are clear that the planet is warming, sea levels are rising, desertification is accelerating, and hundreds of millions of people are likely to face food and water security challenges within the next 30 years. What role can technology play in mitigating these risks? Furthermore, how do climate-related challenges translate into new or evolving missions for the Army?

In addition to identifying trends by mining open-source documents, this report includes data from an inaugural survey of the Army S&T enterprise on the relative degree of risk and opportunity these trends might present, as well as the likely state of U.S. technological leadership in 2047 relative to potential competitors. A total of 862 SMEs contributed data to the survey, and the results were useful in placing the trends into a broader context. They takeaways from the survey data were:

- Opportunity and risk go hand-in-hand. There was a strong correlation between opportunity and risk ratings, suggesting that many of the most promising technologies, such as robotics and artificial intelligence, also carry the greatest risk to future Army forces. The report considered several possible explanations for this relationship, such as the likelihood that the diffusion of innovation could enable future adversaries to capitalize equally on breakthrough technologies. The survey was not designed to dig into this connection. However, a follow-on study of the link between emerging technological opportunities and risks could give Army leadership better context for guiding deep future capability development.
- Opportunity and risk are also asymmetric. SMEs viewed several trends, including robotics and AI, energy technology, advanced materials and manufacturing, quantum computing, and mixed reality as presenting relatively greater opportunity than risk. In contrast, biomedical science and human augmentation, food and water technologies, synthetic biology, space technologies, and technologies for climate change adaptation were viewed as sources of more risk than opportunity. This asymmetry points to the importance of weighing both risk and opportunity in thinking about emerging technologies. There is often a tendency to view technology from the perspective of what it offers – the opportunities it presents, and how those opportunities might be maximized. However, it is also vital to consider technology as a source of risk to shape an appropriately nuanced S&T strategy.
- Continued technological dominance is not guaranteed. On average, SMEs believed that the United States is likely to maintain a technological edge in most of the trend domains through 2047. The exceptions were climate change adaptation technology, for which SMEs estimated the U.S. would lag other nations, and technologies related to food and water security and synthetic biology, for which SMEs estimated the U.S. would most likely be at parity with other nations. However, there was a relatively high degree of variability in SME responses, and the data suggested that broad loss of U.S. technological dominance cannot be discounted. Again, the intent of this survey was to provide a broad view of risk, opportunity, and leadership. Army leadership should conduct a deeper analysis of

the risk of losing our technological lead in these key areas, and what steps might be taken to mitigate that risk.

Taken together, the trends discussed in this report raise several strategic questions for the Army as it looks to evolve a resilient strategy for the coming decades:

- How should emerging technologies, such as those discussed in this report, get factored into Army wargames? In particular, how can we rigorously wargame emerging technologies that are currently at a low technology readiness level, and therefore difficult to represent via modeling and simulation?
- Do we have the necessary tools and processes to perform sustained technology reconnaissance to inform senior leaders in charge of creating doctrine and setting R&D investment priorities? Is the Army doing enough to leverage trend analysis and strategic foresight capabilities resident in the joint service community and among allies?
- Barring major improvements in the acquisition process, how can the Army benefit more rapidly from technological innovation, particularly by leveraging commercial research and development efforts?
- Assuming innovation becomes globalized, how can the Army better work with foreign governments and international research and development centers to ensure that the Army has access to the best available technology, which might very well come from outside the United States?
- How can the Army better partner with the joint community, international partners, NGOs, and other stakeholders to influence government and industry-backed R&D agendas to a) deliver new capabilities for maintaining security, b) prevent adversaries from co-opting technological innovation to their own ends, and c) prevent many of the potential "dark sides" of S&T trends from creating new security challenges?
- How can the Army foster emerging innovators, including start-ups, that fall outside the traditional defense industrial base? On the flip side, how can the Army encourage innovation at its own research and development centers?

Science and technology will undoubtedly transform many aspects of life over the next 30 years. While it is impossible to accurately predict the future in detail, the trends discussed in this report will likely influence the course of the world, with important ramifications for the U.S. Army. The intent behind this report was to inform Army leadership about where the future might be headed and raise questions about how we might best prepare the force for a dynamic and uncertain future. Technological change will present both challenges and opportunities for the Army and the nation in the coming decades. Strategic thinking will be critical for understanding how to capitalize on S&T trends to prepare the force for the road ahead.

APPENDIX A: TREND SOURCES

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APPENDIX B: ANALYSIS METHODS

Trend Identification Methodology

Emerging S&T trends were identified through a three-step process of scanning published trend forecasts, clustering using semantic analysis to isolate common topics, and coding to identify emerging trends.

Scanning involved a comprehensive literature search for open source trend forecasts published by foreign and domestic government agencies, industry analysts, academic organizations, and think tanks. A total of 52 forecast reports were identified based on the following criteria:

- All of the reports had to be the product of rigorous and well-documented research conducted by reputable organizations with a track record of producing high-quality trend analysis.
- All of the reports had to have been published within the past 5 years (reports published late in 2012 were acceptable).
- All of the reports had to address science and technology trends that could influence Army operations and the future operating environment over the next 30 years.
- All of the reports had to address a wide range of science and technology trends. Narrow forecasts related to highly specific industries or technology domains were not included in this analysis.

Overall, 29 sources were carried over from the 2015 Emerging Trends report, while 23 new sources were added. Each document was carefully reviewed for discussions of emerging trends that are likely to impact science, technology, and the Army over the next 30 years. In all, this review isolated 947 specific trends from the source documents. Text describing each of these “raw trends” was copied from the corresponding source document into a database that was used to synthesize a set of cross-cuting trends for the report.

An initial set of candidate trends was developed using latent semantic analysis (LSA), a statistical approach for identifying similarities among a collection of texts.[188] Among other applications, LSA and related techniques are widely used in search engines to match user queries against website content. For the present analysis, LSA was used to identify clusters of trends that shared a common semantic meaning. This involved 5 steps:

1. Quotes from the trend database were pre-processed to remove punctuation and stopwords, which are common words such as “the” that do have any information value relative to the meaning of the text samples.
2. The text data were then tokenized, which involved transforming each quote into a vector containing all of the unique words that appeared in the quote and counts of word frequency.
3. A term frequency-inverse document frequency (tf-idf) model was then fitted to the tokenized data. Tf-idf is a numerical statistic that measures the importance of a word to a particular text. In this case, tf-idf was used to measure the importance of particular words to each entry in the database. The tf-idf value is proportional to the number of times a word appears in a text, offset by the frequency of the word in the database, which adjusts for the fact that some words are more frequent in general. This approach gives greater weight to unique words that are likely to carry greater meaning, and hence are better reference points for identifying clusters of related data.
4. Results from the tf-idf model were then used to compute the cosine similarity among the trends. Cosine similarity is a measure of the similarity between a pair of texts. In this case, a cosine similarity matrix was created that gave a numerical score for the similarity between every quote in the database.

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188 Evangelopoulos, N., Zhang, X., & Prybutok, V. R. (2012). Latent semantic analysis: five methodological recommendations. European Journal of Information Systems, 21(1), 70-86.

5. Cluster analysis using Ward's method[189] was then used to identify a preliminary set of emerging trends based on the cosine similarity matrix. Unlike other clustering routines such a k-means, Ward's method does not require the analyst to pre-determine the number of clusters. Therefore, it can be used in an exploratory manner to identify the optimal number of clusters within a data set. This cluster identification was the focus of the coding phase, described below.

The initial clusters produced by LSA and cluster analysis were then coded using qualitative analysis techniques to identify the final set of trends for the report. Qualitative coding was necessary to ensure that the trends identified by automated statistical analysis made sense as coherent S&T themes. In principle, this could have been done automatically using a different clustering technique, such as k-means. However, analysis for prior editions of the Emerging Trends report demonstrated that automated clustering tends to produce trends that are not always coherent in meaning. This is because LSA is based on statistical similarities in word frequency across documents, not deep context. The coding involved having experts combine clusters identified through statistical techniques into groupings that had a clear meaning and technical focus. Combining quantitative (LSA) and qualitative coding supported an objective analysis while ensuring that the emerging trends accurately reflected the original source documents.

Coding revealed 10 common science and technology "mega-trends" that have the potential to shape future Army operations and the future operating environment. In addition, six cross-cutting contextual trends were also found that will influence how science and technology could evolve over the next 30 years. While the S&T trends are the focus of this report, the contextual trends provide valuable insight into non-technical forces that are likely to shape research and development priorities among governments, industry, and academia.

Concurrence and Share

Having synthesized a set of emerging science and technology trends, additional analysis was focused on understanding the relative emphasis that these trends received from the source documents. This analysis centered on measuring consensus across the sources for each core trend. Consensus within the source reports for certain trends can be a useful measure for thinking through the likelihood that a given trend will have a tangible impact on the future. From a sampling perspective, trends that are drawing a great deal of attention should have a greater chance of generating broad-based impact than trends that are only mentioned a handful of times. Obviously, frequency is an imperfect metric—experts can fall prey to hype, and technologies that fly unnder the radar of collective wisdom can undergo sudden, disruptive innovation. Nonetheless, frequency-related metrics can help shed additional light on how much attention particular trends are getting among experts within governments, industry, think tanks, and other organizations.

With this in mind, two measures of frequency—concurrence and share—were calculated for each trend. Concurrence measured the percentage of source reports that made mention of a particular trend. Values ranged from 73.08% for Robotics and AI, to 19.23% for quantum computing and space technologies. Figure 3 depicts the concurrence values for the 10 emerging S&T trends.

Share scores measured the number of times a trend appeared in the database that was used to conduct the LSA. Certain trends are discussed multiple times in a given report. Therefore, share provides insight into the relative amount of focus given to each trend across the entire dataset. Put another way, higher share values reflect a larger "footprint" for a trend in the data, which can be viewed as an index of the "mind share" a trend occupies within the professional foresight community Share ranged from 20.37% for Robotics and AI, to 3.44% for Space Technologies. Figure 4 depicts the share values for all 10 emerging S&T trends.

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[189] Everitt, B. S., Landau, S. and Leese, M. (2001), Cluster Analysis, 4th Edition, Oxford University Press, Inc., New York; Arnold, London.

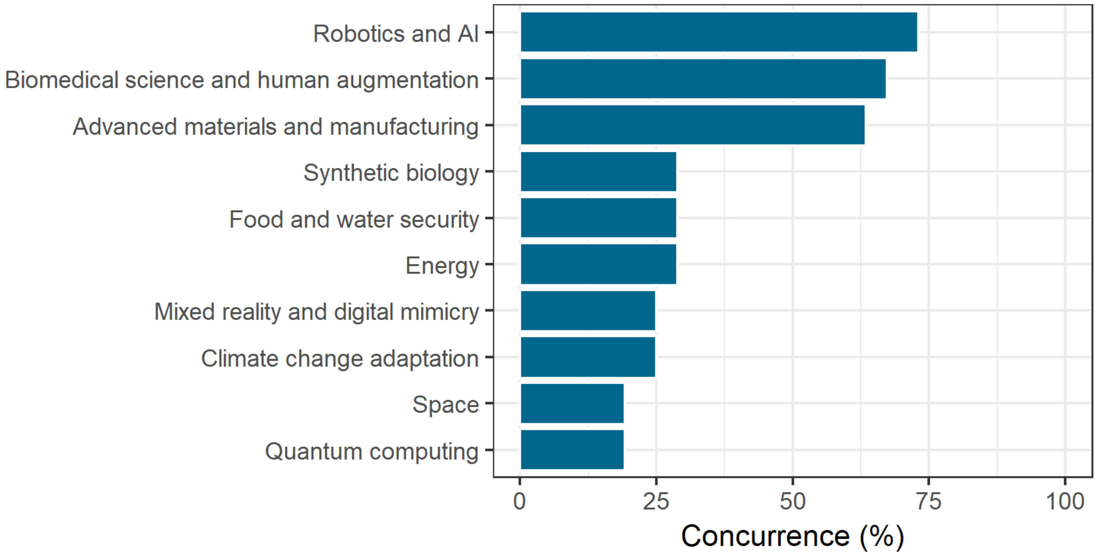


Figure 3. Concurrence scores for the 1- emerging S&T trends. As described in the text, concurrence measures the percentage of source documents that discussed each trend.

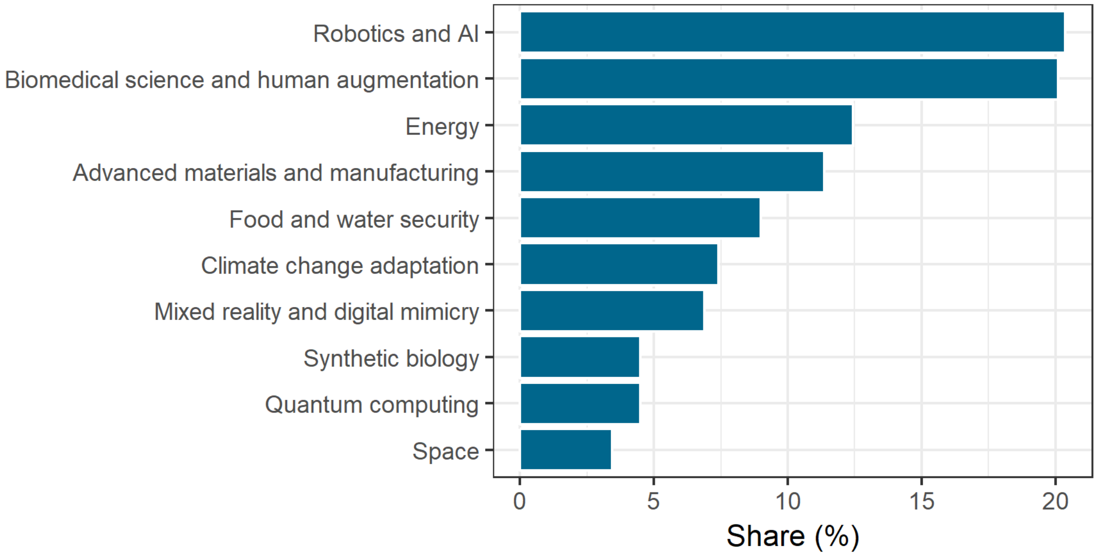


Figure 4. Share scores for the 1- emerging S&T trends. As described in the text, share measures the number of times each trend appears in the database that was compiled from the source documents. Higher share values reflect a larger "footprint" for a trend in the data, which can be viewed as an index of the "mind share" a trend occupies within the professional foresight community.

SME Trend Survey Methods

A survey was conducted to gather subject matter experts' (SMEs) opinions on the relative degree of risk and opportunity that the trends discussed int his report are likely to generate in the next 30 years. The survey was also intended to gauge SME views on the prospects for U.S. technological leadership in 2047.

An electronic survey was distributed to every member of the Army science and technology enterprise through the appropriate chains of command for the Research, Development, and Engineering Command (RDECOM), the Medical Research and Materiel Command (MRMC), the Army Research Institute for the Behavioral and Social Sciences, and the Engineer Research and Development Center. Organizations were tasked to distribute the survey to their science and engineering staff. The survey was also sent to TRADOC (with a request for wide distribution) and members of the Technology Wargaming community outside DoD. A total of 869 SMEs completed at least a portion of the survey. Participation was voluntary and respondents were free discontinue survey completion at any time. Responses were anonymous. The survey was divided into three sections: demographics and background, risks and opportunities, and technical leadership.

The demographics and background section was intended to collect basic information on organizational affiliation, professional role, and technical background. This data is available upon request. Participants were asked the following questions in this section:

- Which of the following best describes your primary professional role? (Response options: Scientist, Engineer, Training/Training Development, Capabilities Development, Concept Development, Program/Project Management, Management/Leadership, Intelligence)
- Which of the following best describes your primary workplace? (Response options: U.S. Army lab or RDEC, Other DoD R&D facility, TRADOC, College or university, Industry, Think tank)
- If respondents selected "U.S. Army lab or RDEC", they were then asked to choose their specific organization from a list of organizations that included all labs and RDECs across RDECOM, MRMC, ERDC, SMDC, and ARI.
- If respondents selected TRADOC, they were then asked to choose their specific organizations from a list of TRADOC components.
- How many total years of professional experience do you have?
- What time horizon does your work primarily influence? (Response options: 0-5 years out, 6-10 years out, 11-20 years out, greater than 20 years out)
- How would you rate your level of technical expertise in each of the following science and technology topics? (Participants were shown a list of the 10 S&T trends and asked to rate their expertise on a 5-point scale ranging from Novice (limited or no technical expertise) to Expert (formal education and specific technical expertise)).

The Risks and Opportunities section of the survey asked participants to forecast the potential degree of risk and opportunity each trend is likely to present by 2047. Participants were asked two ranking questions:

- Please rank the following trends by the level of risk each is likely to pose for the U.S. Army by the year 2047.
- Please rank the following trends by the level of opportunity each is likely to create for the Army by the year 2047.

Both questions provided a drag and drop interface that enabled participants to order the trends from highest to lowest risk/opportunity.

The final section of the survey asked participants to estimate the likely technical position of the United States in 2047, relative to major global competitors. Respondents were shown a list of the 10 S&T trends and asked to answer the following question for each trend using a 5-point scale with the following anchors: Significantly Behind, Equal, Significantly Ahead.)

ROBOTICS, AI, AND AUTONOMOUS SYSTEMS

OFFICE OF THE ASSISTANT SECRETARY OF THE ARMY
ACQUISITION, LOGISTICS & TECHNOLOGY

By 2047, robots and autonomous systems are likely to be commonplace. Autonomous vehicles will make transportation safer and more efficient, while possibly fueling the rise of the sharing economy. Robots will care for the elderly, deliver groceries, harvest crops, maintain public infrastructure, and provide many other services that touch everyday life. Artificial intelligence software will extract insights from terabytes of data, automate business processes, and step into customer service, teaching, and other roles traditionally seen as "people-centric". However, the rise of AI and robotic systems could displace hundreds of millions of labor and service workers, creating economic instability and the risk of social unrest. Networked autonomous systems will also become an attractive target for adversaries and a new priority for cyberdefense. The use of robots in military operations will expand as robotic systems gain mobility, dexterity, and intelligence, making robots effective partners on future battlefields. At the same time, adversaries will use robots and autonomous systems in ways that challenge us ethically and tactically.

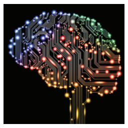
ENABLING S&T

» Machine Learning
Learning is critical for autonomous systems to adapt to novel, complex environments. Impressive strides are being made in deep learning, inspired by a growing understanding of how learning occurs in biological nervous systems.

» Sensors and Control Systems
To interact safely, usefully, and effectively with humans in real-world environments, robots and other autonomous systems will need richer internal models of their environments linked with more flexible movement capabilities.

» Human–Machine Interaction
Research is needed on techniques for interaction between autonomous systems and people in complex, real-world tasks. Research on natural language communication and empathic robots could help bridge the human-machine divide.

SIGNALS



» Self-Taught AI
Researchers from the University of Leicester have developed the foundations for algorithms that could allow AI to correct errors in real-time without affecting existing skills. This could give autonomous systems the ability to self-correct errors instantaneously and accumulate knowledge by learning from mistakes.

» Interactive Robogami
Researchers at MIT have demonstrated a system they call "Interactive Robogami" that enables users to design a robot in minutes. The designs can by 3D-printed and assembled in as little as four hours.

» AI Inventors
Researchers at Carnegie Mellon University and the Hebrew University of Jerusalem have developed a technique that enables AI to mine databases of patents and research papers to identify analogies between different technical methods and problems. The system can use analogous thinking to solve different problems and create new products.

IMPACTS

» Social
Robots will become part of the social landscape. As autonomy and intelligence grows, these systems will raise difficult questions about the role of personal responsibility and "machine rights". Loss of jobs to automated systems could lead to significant social unrest.

» Political
As robots become integrated into society, governments will face challenging legal and regulatory issues around how much autonomy robots should be granted and how to assign responsibility when robots break the law.

» Economic
Robotics and AI will continue to transform work, eliminating the need for a wide variety of manual labor and taking over many service jobs. While the gains in efficiency and cost will be a boon for global markets, the loss of jobs across multiple industries will create significant pressure on economies worldwide. A recent study by a pair of Oxford University economists found that machines could eliminate 47% of jobs across every economic sector.

» Environmental
As autonomous systems become more prevalent, it will also become important for robots and AI to be capable of coordinating with each other. Research on swarm robotics demonstrates how robots and other autonomous system might communicate and cooperate.

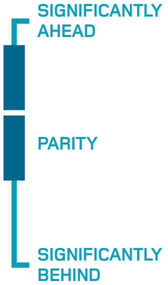
» Defense
As autonomous systems become more capable, the U.S. Army will have to reevaluate the role of the Soldier in combat. Potential adversaries will also use robotic systems, and they might be willing to go further than the United States in giving combat robots complete autonomy.

20.37%
SHARE

#1
OPPORTUNITY

73.08%
CONCURRENCE

#1
RISK



ADVANCED MATERIALS AND MANUFACTURING

OFFICE OF THE ASSISTANT SECRETARY OF THE ARMY
ACQUISITION, LOGISTICS & TECHNOLOGY

Over the next 30 years, nanomaterials and other novel materials such as metallic foams and ceramic composites will be found in clothing, building materials, vehicles, roads and bridges, and countless other objects. The Army will be able to leverage advanced materials to produce lighter, stronger body armor, more efficient vehicles and shelters, and more robust batteries and renewable energy systems. It is also highly likely that 3D printers will be able to print objects that incorporate multiple materials, enabling additive manufacturing of electronic circuits, batteries, and other complex devices and components. Military logistics will likely become streamlined, as equipment and supplies will be printed directly at their point of use. Objects will become information, and digital piracy could replace shoplifting. The proliferation of low-cost 3D printing technology also poses potential threats. It is highly likely that terrorists and criminal organizations will print weapons, sensors, and other equipment using raw materials that are difficult to track on the open market. In fact, 3D printed firearms are already generating significant public controversy and new challenges for law enforcement.

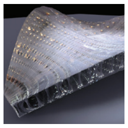
ENABLING S&T

» Multi-Material Printing
Most 3D printers currently on the market print objects from ABS or PLA plastic filament. Higher-end production printers can also use metal podwers. Future applications will require printers that can combine a wide range of materials to create complex objects.

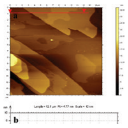
» 4D Printing
4D printing uses additive manufacturing techniques to create objects that can change shape in response to heat, light, mechanical force, or electrical signals. This technology is at the basic/early applied stage, but holds great promise.

» Graphene Production
Graphene has the potential to transform electronics, but a major barrier to graphene application has been the inability to tune graphene composites to produce materials that perform reliably and that can be manufactured at scale in a cost-effective manner.

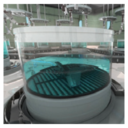
SIGNALS



» 4D Printing
Scientists at Singapore University of Technology and Design have recently discovered a way to rapidly produce 4D printed materials using memory polymers that change shape when heat is applied.



» Superconductors from Biomass
Researchers at Qilu University of Technology in China, have developed a method for turning leaves and other biomass waste into a porous carbon material that acts as a supercapacitor three times more effective than some graphene supercapacitors.



» Growing Drones in a Vat
BAE Systems and Scotland-based Cronin Group PLC are working on technology for "growing" drones by assembling them at the molecular level. Eventually, this technology could be used to rapidly produce drones using complex materials.

IMPACTS

» Social
3D printing, combined with social media technology, could move "maker" culture into the mainstream. People will be able to collaborate, customize, and share design files in ways that will be difficult to predict or control. Novel materials will improve consumer electronics, improve medical treatment, and improve access to reliable sources of renewable energy.

» Political
3D printing raises serious questions around protecting intellectual property. Imagine the complexity of policing online piracy of music, movies, and software. Now apply the same difficulties to every physical object.

» Economic
Additive manufacturing will make it possible to do low-rate production and customization cost-effectively. Nanomaterials have the potential to transform many industries, ranging from electronics to automotive manufacturing.

» Environmental
Point of use production via 3D printing could reduce pollution from transporting goods across countries and continents. On the other hand, the environmental effects of nanomaterial pollution are currently unkown, and could be extremely detrimental to fragile ecosystems.

» Defense
3D printers could transform military logistics by allowing units to print equipment and spare parts in the field. At the same time, adversaries will be able to print weapons and other equipment from plans that are stolen, reverse-engineered, or or traded on illicit networks. Advanced materials will likely lead to better batteries and improved body armor.

11.38%
SHARE

#2
OPPORTUNITY

63.46%
CONCURRENCE

#5
RISK

ENERGY TECHNOLOGY

Over the next 30 years the global demand for energy is projected to grow by 35%. The development of methods like fracking and directional drilling have opened vast new reserves of oil and natural gas. These technologies have up-ended global oil markets and turned the United States into one of the world's largest fossil fuel producers. At the same time, renewable energy sources such as solar and wind are rapidly approaching cost-parity with fossil fuels. In the past two decades, the cost of power produced by solar cells has dropped from nearly $8 per watt of capacity to less than one-tenth of that amount. Nuclear power, is also expanding, with new reactor designs promising greater safety and less radioactive waste. While adoption of cleaner energy sources would help combat global climate change, new frictions will emerge over access to rare materials used in batteries, solar cells, and other linchpins of the energy revolution. The fading of fossil fuels also carries significant risk of economic and social destabilization across the Middle East and North Africa, presenting new security challenges for the United States and its allies.

ENABLING S&T

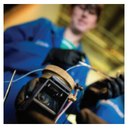
» Solar Efficiency
Research into new materials continues to increase the efficiency of solar panels while reducing their cost. At current growth rates, the cost per watt of solar could drop below 50 cents over the next 20 years.

» Battery Technology
Batteries are key to managing uneven power output at solar and wind generation facilities. Battery researchers are exploring new chemistries that can store greater amounts of power in less space and for lower cost.

» Energy Harvesting
The planet is awash in energy. Beyond solar, wind, and biofuels, research and development projects are expanding our ability to harvest energy from geothermal heat, tidal power, and other unconventional sources.

SIGNALS

» Ultra-Efficient Solar Cells
Researchers from George Washington University recently reported on a multi-layered device that uses lenses to concentrate sunlight onto tiny solar cells. It can utilize energy from long-wavelength photons that conventional cells cannot, and it works with 44.5% efficiency, compared with 25% efficiency of today's most common solar cells



» Solar Fuels
Scientists at CalTech and other institutions are developing "solar fuels" through processes that mimic photosynthesis. The technology uses a catalytic membrane that absorbs sunlight, CO2, and water to secrete liquid or gas fuels.

» Solid-State Batteries
Engineers at the University of Texas at Austin recently reported on new all-solid-state cells that have three times the energy density as lithium-ion batteries. In addition, the new batteries are noncombustible, have a long life, and charge and discharge quickly.

IMPACTS

» Social
As a global middle class emerges, power and energy will become the glue that keeps civil societies together. Conversely, countries with less access to clean sources of energy could face social strife as their economies stall.

» Political
Climate change and environmental risks from nontraditional fossil fuel extraction will drive global political debates over the role of oil and natural gas versus expanded use of renewable energy sources.

» Economic
Domestically, the discovery of massive oil and natural gas reserves will bolster the US economy. Globally, the emergence of renewable fuels will spark new industries and reduce barriers to power generation in developing nations.

» Environmental
Oil and coal will still provide the bulk of the global energy budget through at least the 2030s. Continued reliance on fossil fuels will increase atmospheric CO_2, driving additional climate change. Negative effects could be offset by alternative energy technologies that are cost-competitive with fossil fuels.

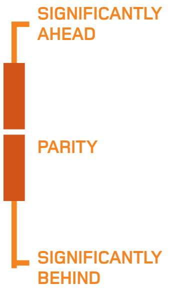
» Defense
The prospect of US energy security will significantly reshape the strategic environment. While we become less dependent on foreign sources of energy, traditional oil- producing powers could experience significant economic disruption, opening the door for extremist ideologies to take root.

12.43%
SHARE

#3
OPPORTUNITY

28.85%
CONCURRENCE

#2
RISK



BIOMEDICAL SCIENCE & HUMAN AUGMENTATION

Over the next 30 years, technology will transform medicine and enable people to transcend biological limits on human potential. Genomics will give rise to personalized medicine, with treatments for cancer, cardiovascular disease, Alzheimer's, and other diseases tailored to individual genetics. Artificial organs will be grown for transplantation from DNA samples, eliminating wait times for life-saving transplants and the risk of organ rejection. "golden hour" for wounded Soldiers. Exoskeletons and brain-interfaced prosthetics will make us stronger and restore mobility to the elderly and infirm. At the same time, the cost of advanced medical care will stress many national health care systems and trigger rising inequality in access to life-saving treatments. Likewise, augmentation technologies will come at a price, and those who cannot afford to upgrade their "human chassis" might find themselves unable to compete in the augmented economy. Networked augmentations will also be an appealing target for hackers looking to control over our very minds and bodies. While the U.S. Army will benefit from augmenting its Soldiers, the force will face adversaries who are similarly enhanced, and an augmentation arms race could evolve.

ENABLING S&T

» Regenerative Medicine

Research is underway that will enable organs, and potentially entire limbs, to be grown from a patient's own genetic material.

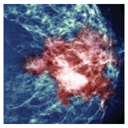
» Exoskeletons and Prosthetics

Exoskeletons are undergoing rapid development, with research and development focused on new control architectures, power for sustained operation, and optimizing the human-system interface. The ability to interface prosthetics directly with the human nervous systems is also rapidly improving.

» Personalized Medicine

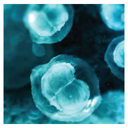
Pharmaco-genetics could usher in an era of personalized medicine. Detailed understanding of human genetics will enable the development of individualized pharmaceuticals for cancer, autoimmune disorders, neurodegenerative diseases, and other life-threatening ailments.

SIGNALS



» AI Pathologist

PathAI, a startup founded by faculty from MIT and CalTech, has created an AI that can diagnose breast cancer nearly as well as human doctors. The team was able to demonstrate that teaming a pathologist with the AI reduced diagnostic error by 85 percent.



» Cell Reprogramming

A team of scientists from the Ohio State University has developed a technique for in vivo cell reprogramming that could offer a new option for delivering regenerative treatments. The technology involves applying a chip that creates "nanochannels" in tissue using an intense, focused electric charge. A therapeutic package of DNA or RNA can be precisely delivered through these channels into diseased tissue.

» TaLOS

In 2018, the U.S. Special Operations Command is scheduled to test an early, but fully functional version of its Tactical Light Operator Suit.

IMPACTS

» Social

Society will largely benefit from healthier, more active populations, but there will be rising tensions over access to costly medical interventions. Augmentation tech will be costly, leading to a two-tiered world of enhanced "haves" and "have nots". This could create social unrest.

» Political

Access to life-saving medical technology will place significant stress on health care systems around the world, leading to difficult political decisions about health care financing, patent protection for pharmaceuticals, and the legal limits of medical intervention.

» Economic

Workers will remain productive well into their 70s and beyond. The market for augmentation technology will drive growth across multiple economic sectors, including health care, manufacturing, defense, education, and services.

» Environmental

The potential environmental impacts of biomedical and augmentation tech are unclear, though longer-lived populations will create more waste and create challenges for sustainability.

» Defense

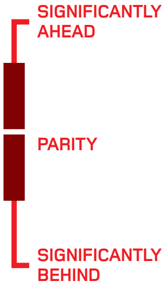
Regenerative medicine and other breakthroughs will transform battlefield medicine, extending the golden hour and allowing troops to recover from injuries faster. The Army should expect to face adversaries that use augmentation tech. Networked augmentations, such as exoskeletons and prosthetics, could be the target of cyberattacks.

20.11%
SHARE

#4
OPPORTUNITY

67.31%
CONCURRENCE

#3
RISK



QUANTUM COMPUTING

Quantum computing uses properties of subatomic particles like superposition and entanglement to represent and manipulate data. While the technology has been discussed as a theoretical possibility for decades, recent research efforts across academia, industry, and government labs are beginning to demonstrate quantum systems that might have practical applications in the next 5-15 years. Quantum computing could be a linchpin technology that revolutionizes multiple other technical domains such as climate modeling, pharmaceutical research, and materials science. Quantum computing could also revolutionize cryptography. A quantum computer could crack all current encryption methods, and quantum cryptography could provide the first truly unbreakable encoding technology. Recent research has begun to overcome many of the technical problems that have limited the development of practical quantum computers. While real-world applications of quantum computing might not be seen until the mid-2040s, an influx of investment by governments and industry signals that quantum computing might be approaching a tipping point.

ENABLING S&T

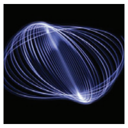
» Quantum Error Connection
Qubits, the fundamental unit of quantum computation, are extremely fragile, and tend to "decohere", resulting in data loss. The field of quantum error correction examines how to stave off decoherence and other errors.

» Quantum Programming
Programming a quantum computer is very different than working with traditional computers, and development of quantum programming methods is an active area of research.

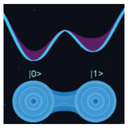
» Post-Quantum Cryptography
Through at least 2040, the majority of networked systems will still use traditional encryption methods that will be increasingly vulnerable quantum decryption. This emerging risk has led the National Institute of Standards and Technology to push for investment into "quantum resilient" systems.

SIGNALS

» New Quantum Computers Coming Online
IBM opened a 5-qubit quantum-computing platform to the public for experimentation in summer 2016, and the company recently announced that it had built and tested 16 and 17-qubit systems. IBM plans to build a roughly 50-qubit system within the next few years, while a Google team aims to build a 49-qubit integrated circuit by the end of 2017.



» Long-Distance Entangled Photons
A group of Chinese researchers used a satellite to beam entangled pairs of photons to three ground stations, each more than 1,200 km apart.



» Qudits
Qudits, rather than qubits, may enable more efficient and error-tolerant computation. In a qudit, a photon may have a superposition of more than two states, and a few qudits could do the same work as many more qubits. An international team of researchers recently created a microchip containing two qudits, each with 10 states.

IMPACTS

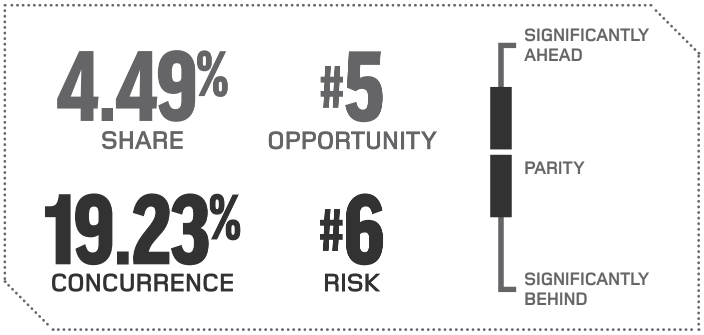
» Social
Quantum computers will enable rapid calculations on massive data sets that are impossible today. This could affect medical research, enhance big data analytics, and protect individuals and societies from cybercrime.

» Political
The ability of quantum computers to crack commercial encryption will lead to significant political concerns over privacy and cybersecurity. Bank accounts, email, and any other data not secured using quantum cryptography will be open to cyberattack.

» Economic
Economic impacts of quantum computing will be felt in financial modeling, logistics, engineering, health care, and telecommunications. Quantum computers would solve analysis problems within seconds that currently require days or months of supercomputing time.

» Environmental
The massive processing power of quantum computers would revolutionize climate modeling and lead to far more accurate forecasts of weather and climate change.

» Defense
Quantum cryptography will transform information security and signals intelligence. Adversaries using quantum computers would be able to crack traditionally encrypted systems used by the U.S. or our allies.



4.49% SHARE

#5 OPPORTUNITY

19.23% CONCURRENCE

#6 RISK

MIXED REALITY AND DIGITAL MIMICRY

Mixed reality is the fusion of real and virtual worlds through immersive technologies including virtual reality (VR) and augmented reality (AR). At present, commercial applications are largely focused on immersive gaming and educational visualizations. However, as technology continues to evolve it is likely that VR and AR will become standard technologies across a range of industries. For example, augmented reality could enhance a surgeon's ability to visualize internal anatomy and anticipate potential complications during delicate operations. VR and AR could also be used in construction and maintenance, overlaying schematics, technical data, and other information directly onto real-world objects. Rapid progress is also being made in technology that renders high-fidelity, fully-animated models of specific people. This technology could be used to create rapidly model important public figures. Off-the-shelf 3D modeling and animation software could be used to manufacture videos that undermine public communications or paint leaders in a negative light. Information warfare is likely to become significantly more complicated, as digital mimics take center stage in the battle for controlling strategic narratives.

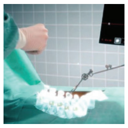
ENABLING S&T

» Consumer-Grade Hardware
In the past two years. Microsoft, Facebook, Sony, and Samsung have all entered the virtual reality market with a focus on building affordable, high-definition VR/AR displays.

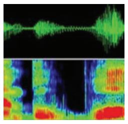
» Blended Experiences
Creating immersive, multisensory mixed reality experiences requires converging research in computer graphics, wireless motion tracking, computer vision, and human perception.

» Interaction Techniques
New methods of interacting with VR and AR, including gestural interfaces and reality-based user interfaces, are currently being developed that should allow users to act within virtual and augmented spaces just as they do in the real world.

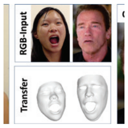
SIGNALS



» Medical AR
Scopis, a Cambridge, Massachusetts-based developer of augmented reality software, is at the forefront of the emerging medical AR sector with an application that projects a mixed-reality overlay on a patient that helps doctors track surgical tools and implants.



» Hacking Voice Authorization
In 2015, researchers at the University of Alabama demonstrated that state-of-the-art voice verification technologies – the kind that are increasingly being deployed by banks and credit card companies – failed to reject up to 90% of fake voices generated by an off-the-shelf voice synthesizer.



» Digital Puppets
In 2016, computer scientists in Germany demonstrated Face2Face, a tool that uses 3D face mapping technology to turn video recordings of real people into virtual "puppets" that can be controlled in real time.

IMPACTS

» Social
Mixed reality will open new channels for people to travel (virtually) and engage with different cultures. At the same time, increasingly immersive experiences could become more attractive than the real world for many people, potentially fueling addiction and withdrawal.

» Political
Mixed reality technologies will almost certainly include networked cameras, leading to new concerns over privacy, identity theft, and state surveillance. Governments may come under pressure to regulate virtual and augmented reality to protect individuals, businesses, and public agencies from blended reality-based violations.

» Economic
Investment in mixed reality technology accelerating, with an estimated market size of $600 billion by 2025.

» Environmental
Mixed reality might have an indirect effect on environmental awareness by making virtual eco-tourism and immersive environmental educational more widely available.

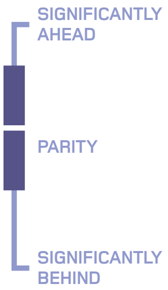
» Defense
The U.S., U.K., and other nations have invested in virtual and augmented reality technologies for decades. In the past, technical limitations have prevented mixed reality from being practical outside of training environments and other limited applications. However, with commercial innovation rapidly improving both hardware and software it is likely that the Army will soon be able to deploy VR and AR systems to the battlefield, revolutionizing how Soldiers access information and conduct operations..

6.79%
SHARE

#6
OPPORTUNITY

25.00%
CONCURRENCE

#9
RISK



TECHNOLOGY FOR FOOD AND WATER SECURITY

Over the next 30 years, inadequate access to food and fresh water will become a crisis point in many parts of the world. Roughly 25% of current farmland is already degraded from overfarming, drought, and air/water pollution. Under optimistic forecasts, prices for staple grains could rise by 30% over the coming decades—increases of 100% are not out of the question if climate change, demand patterns, and failed resource management continue on current trajectories. By 2045, 3.9 billion people—over 40% of the world's population—could face water stress. Technology offers many potential solutions to food and water crises. Desalination, micro-irrigation, water reclamation, rainwater harvesting, and other technologies could relieve pressure on fresh water supplies. Genetically modified crops and automation could improve crop yields and allow farmers to produce more nutrition from less land. Food and water, long taken for granted in the developed world, will become a major focus for innovation, and could become a major flashpoint for conflict.

ENABLING S&T

» Agricultural Technology
Research on transgenic crops could improve drought and disease-resistance. Technologies like robotic automation and micro-irrigation (which improves water delivery to crops by 32-95%) could make farming more resource efficient and productive.

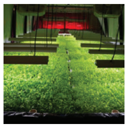
» Water Reclamation and Harvesting
In addition to improved desalination technology, development is underway on filtration systems that can produce potable water from nontraditional sources such as rainwater and muddy or contaminated water.

» Alternative Food Sources
Closed-system hydroponics, vertical urban farms, and other new technologies are enabling crops to be grown without access to arable land. Lab-grown meat could improve access to protein without the environmental and resource impact of raising animals for meat.

SIGNALS

» Analytics for Agriculture
Monsanto-owned The Climate Corporationenables farmers to visualize weather, yield, field health, and nitrogen data for their fields, receive customized planting schedules, and connect a wireless device to their tractors to collect and transmit data about their activities.

» Harvesting Water from Fog
Fog-harvesting mesh nets can collect clean atmospheric water in areas with suitable climates, such as the coastal mountains of Chile, Peru, and Ecuador. Researchers at MIT and their colleagues in Chile have worked to optimize the performance of these nets.



» Urban Farming
The Plant Chicago is a test bed for closed-loop, net-zero-energy urban farming. It features an aquaponics system that produces vegetables and fish, a brewery, bakery, and more. In The Plant, the waste from one process becomes raw material for another.

IMPACTS

» Social
Food and water are essential to human life, and disruptions to these vital resources could have significant social impacts, leading to loss in trust in civil governments, rioting, theft, and hoarding.

» Political
Land and water management is likely to become an important focus for domestic and international politics over the next 30 years. With over 500 rivers and aquifers shared by two or more nations, transnational water control could become a flashpoint. Nations that have historically provided food aid might have to pull back on agricultural exports to feed their own populations.

» Economic
Food and water technologies will be a growth industry over the next 30 years. At the same time, food and water shortages could worsen economic instability and exacerbate class divisions. Today, the world's poor get by on 5-10 liters of water per day, while members of the growing global middle and upper classes use 50-150 liters daily.

» Environmental
Genetically modified organisms (GMOs) have the potential to boost agricultural yields in the face of drought, disease, and degraded farmland. However, the environmental impact of GMOs is uncertain, and many worry that transgenic crops could damage ecosystems if released into the wild.

» Defense
Food and water crises represent dangerous flashpoints for conflict. Some of the world's poorest regions are the most vulnerable to pressures on agricultural output and fresh water supplies caused by climate change and population growth.

8.99%
SHARE

#7
OPPORTUNITY

28.85%
CONCURRENCE

#4
RISK

SYNTHETIC BIOLOGY

Humans have manipulated the genetic code of plants and animals through selective breeding and hybridization for millennia – well before Mendel identified the basic laws of heredity or the Avery-MacLeod-McCarty experiment identified DNA as the genetic material. However, as our understanding of genetics has grown it is becoming possible to engineer custom organisms by building new sequences of DNA from scratch. Genetically-modified crops represent the vanguard of this technology, but we are on the cusp of a broader revolution that will turn life itself into information that can be written and rewritten much like computer code. Scientists are already engineering algae that can secrete biofuels and using DNA to encode thousands of gigabytes of data. Over the next 30 years, synthetic biology will give rise to engineered organisms that can detect toxins, create biofuels from industrial waste, and deliver medicine through symbiosis with human hosts. At the same time, synthetic biology represents profound risks, including engineered biological weapons and invasive synthetic organisms that could destroy natural ecosystems.

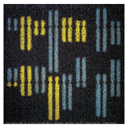
ENABLING S&T

» Modeling and Simulation
Synthetic biology will benefit from better modeling and simulation of of biochemical reactions, how proteins with desired functional properties can be created through engineered DNA, and of interactions among the components of complex synthetic biological systems.

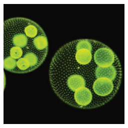
» Standardized DNA
Standardized DNA “biobricks” would accelerate research and development of synthetic organisms by providing scientists with reliable, well-understood foundations for genetic experimentation.

» DNA Synthesis and Sequencing
Technologies like clustered regularly interspaced short palindromic repeats (CRISPR) are giving scientists much greater control over gene sequence editing, and emerging technologies are greatly lowering the cost and time associated with sequencing new copies of DNA.

SIGNALS



» Synthetic Yeast Genome Project
In March 2017, the Synthetic Yeast Genome Project announced it had rewritten 5 of the 16 chromosomes of brewer’s yeast. This synthetic yeast is a promising candidate for producing everything from biofuel to medicines and the researchers optimized the replaced chromosomes for industrial purposes.



» Self-Fertilizing Plants
German chemical giant Bayer and Ginkgo Bioworks are working to re-engineer the symbiotic microbes that allow legume vegetables to create their own fertilizer so they can colonize any plant.

» Safe Genes
DARPA’s Safe Genes program aims to develop gene drives (techniques for encourage uptake of edited genes by cells), along with countermeasures to fight against them and “genetic remediation” tools to reverse their effects.

IMPACTS

» Social
Synthetic organisms will become part of our everyday lives, generating fuel for our cars, keeping our homes clean, and helping us stay healthy through engineered biopharmaceuticals. At the same time, concerns over “playing God” and fears about genetically-engineered superbugs could lead to calls for bans on certain applications of synthetic biology.

» Political
Regulation of synthetic biology is still in its infancy, and very few nations have laws on the books governing research and development of synthetic organisms. Governments could struggle to balance societal and economic benefits of synthetic biology with environmental and other risks.

» Economic
Synthetic organisms could generate inexpensive biofuels, improve industrial processes, and be tailored to deliver medicines through inoculation of human patients. The combined economic impact of these and other applications could be well over $1 trillion per year by 2047.

» Environmental
Invasive synthetic organisms that escape from labs or industrial facilities could devastate natural habitats, destroy crops, and contaminate water supplies worldwide.

» Defense
The Army could benefit from biofuels and biosensors made from genetically engineered organisms. At the same time, future adversaries could develop synthetic biological weapons that are highly lethal, communicable, and difficult to detect.

4.50%
SHARE

#8
OPPORTUNITY

28.85%
CONCURRENCE

#7
RISK

SIGNIFICANTLY AHEAD
PARITY
SIGNIFICANTLY BEHIND

SPACE TECHNOLOGY

Sixty years after Sputnik became the first artificial satellite in Earth orbit, space remains a largely under-utilized frontier. However, recent progress in low-cost commercial space flight, miniaturization, materials, and space propulsion suggest that space will be an important focus of technological innovation over the next 30 years. By 2047, it is likely that humanity will extend its reach beyond Earth orbit. Projects like Google's Lunar XPrize will likely lead to semi-permanent presence on the moon. And while autonomous rovers will likely remain the vanguard for interplanetary exploration, it is possible that humans will step foot on Mars within 30 years. It is also possible that innovation will make asteroid mining both technically feasible and economically viable, making available trillions of dollars in resources that are increasingly vital for modern civilization. As the number of space-faring nations increases, dependence on space-based telecommunications, global positioning, weather forecasting, and defense will likely make space a new domain for international competition, and potential conflict. Space debris could become a significant problem for criticial orbital infrastructure.

ENABLING S&T

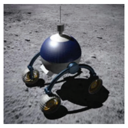
» Reusable Launch Vehicles
SpaceX recently demonstrated a rocket booster that can land back on earth after launch. Continued innovation in reusable launch components is necessary to make routine space travel cost-effective.

» Autonomous Space Vehicles
Robots have tremendous potential for exploration and commercial ventures such as asteroid mining. The long lag times in communication with off-world robots calls for ongoing innovation in machine intelligence.

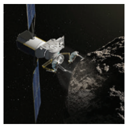
» Resilient Space Systems
Space stations and satellites are often physically fragile, and high-velocity impacts with meteorites and space debris will become a growing problem. Advances in material science could make space assets more durable, while robots could provide a solution for effecting repairs in the harsh environment of space.

SIGNALS

» Reusable Rockets
SpaceX, the poster child for the emerging private space economy, has demonstrated a reusable version of its Falcon 9 rocket that can return to Earth after launch. This technology would significantly reduce the cost of orbital launches.



» Lunar XPrize
Google's Lunar XPrize offers up to $20 million to the first privately-funded team to land a spacecraft on the surface of the moon, move it 500 meters across the lunar surface, and beam high-definition video and images back to Earth. Five teams from around e world have advanced in the competition and have approvals to launch payloads into space this year.



» Venture Capital Looks Skyward
Private investment in space technology is growing rapidly – venture capital investment in the sector was $1.8 billion in 2015, double the amount made in the previous 15 years combined.

IMPACTS

» Social
Apart from space tourism, which is likely to remain a luxury through 2047, the social impacts of space technology will largely be indirect, in the form of better communications, more reliable meteorology and geologic data, and more precise GPS. Asteroid mining could increase access to technology by lowering cost of raw materials.

» Political
International collaborations are likely to become more important, as more countries deploy satellites and other space-based assets. New space races could be fueled by the economic incentives of harvesting extraplanetary resources.

» Economic
The declining cost of space travel will likely fuel rapid growth in commercial space investment. Much like the Space Age, innovations in this area could generate significant spin-off technologies that drive economic development.

» Environmental
Satellite technology could be used to generate more reliable environmental data. It is possible that solar shields could be used to reduce global warming. Asteroid mining could reduce the environmental impacts of terrestrial mines.

» Defense
Growing dependence on space-based infrastructure could lead to new frictions here on Earth. As more nations come to rely on space-based assets the control of space could become a significant flash point. The militarization of space is not out of the question, and anti-satellite warfare could have profound effects on the U.S. Army, which relies heavily on satellites for secure global communications, intelligence gathering, and coordinating joint maneuver.

3.44% SHARE

#9 OPPORTUNITY

19.23% CONCURRENCE

#10 RISK

TECHNOLOGY FOR CLIMATE CHANGE ADAPTATION

By 2050, the average global surface temperature is forecast to rise between 2.5 and 5.4 degrees Fahrenheit, and sea levels could rise up to 6.6 feet by the end of the century. Left unchecked, climate change on this scale could threaten agriculture, put added pressure on fresh water supplies, and expose many coastal cities to destructive storms and flooding. Technology could play a role in mitigating the worst dangers associated with climate change. By 2047, it is highly likely that coastal areas will use man-made wetlands, storm barriers linked to oceanographic sensors, and 4D-construction techniques to improve climate resiliance. Commercial carbon capture and sequestration facilities could scrub CO_2 and other greenhouse gases such as methane from the air, producing fertllizers, plastics, and other useful resources. More radical attempts at geoengineering may become necessary, such as seeding the atmosphere with aerosol particles that reflect sunlight, or screening the Earth behind orbital solar shields. Many large-scale geonegineering concepts are theoretical, and the second and thrid order effects of techniques such as atmosphereic seeding are poorly understood.

ENABLING S&T

» Carbon Capture and Sequestration (CCS)
CCS removes carbon dioxide from the atmosphere, reducing the primary cause of global warming. Direct carbon capture from the air is technically feasible today, but scaling these technologies will require solving a variety of engineering challenges.

» Solar Radiation Management (SRM)
SRM involves spraying sulfate aerosols into the stratosphere that reflect solar radiation, reducing surface temperature. SRM is promising, but basic research is needed to better understand possible atmospheric interactions and effects on weather patterns.

» Sensors and Real-Time Data
Research is needed on how sensors and responsive robotics could be used to control hydrologic environments and assist in rebuilding natural coastal defenses.

SIGNALS

» Hardening Governor's Island
New York City built a ring of man-made hills around Governor's Island to protect the popular park from increased coastal flooding due to sea level rise and strengthening hurricanes such as Sandy, which flooded much of lower Manhattan in 2012.

» Commercial Carbon Capture
Swiss company Climeworks has developed the first commercial carbon capture plant. The facility scrubs carbon dioxide from the air and converts it to fertilizer.

» First Large-Scale Test of SRM
Dr. David Keith of Harvard is on track for a pioneering small-scale experiment injecting reflective particles into the atmosphere. Plans include testing different materials (e.g. sulfur dioxide, alumina, calcium carbonate), and measuring their reflectivity and reaction with other atmospheric compounds.

IMPACTS

» Social
Climate change could drive new waves of migration and exacerbate many of the tensions the world is currently experiencing around refugee status and immigration. Climate adapation technologies have broad implications for property rights and eminent domain, and such projects could spark public backlash in some parts of the world.

» Political
Large-scale geoengineering would have global effects, and the cost of such interventions would likely require international partnership. There are limited frameworks in place for negotiating and funding geoengineering projects, and the potential for unforeseen consequences could create domestic and international political opposition.

» Economic
Left unchecked, climate change is highly likely to damage the world economy. Developing nations are particularly vulnerable to climate-related economic harm. On the other hand, technologies like commercial carbon sequestration could create new markets and industries, fueling economic growth.

» Environmental
The long-term effects of climate adaptation techniques are largely unkown. Even seemingly innocuous interventions, such as wetland restoration, could have unanticipated environmental effects. Better real-time analytics and environmental modeling could help reduce risk.

» Defense
The Department of Defense recognizes climate change as an accelerant of instability. Defense forces will likely be on the front lines of disaster relief and humanitarian assistance operations driven by climate change.

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