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

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Emerging Science and Technology Trends: A Synthesis of Leading Forecasts

5th Edition

EXECUTIVE SUMMARY

This is the fifth edition of the Science and Technology Emerging Trends report, published annually by the office of 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.

As with prior editions of this report, the overall approach was to synthesize all of the current open-source horizon scans published by U.S. and international government agencies, industry leaders, think tanks, and other organizations that maintain a close eye on S&T trends. A total of 48 reports were included in this synthesis, which yielded a database of over 480 trends related to science and technology and over 120 trends related to broader contextual factors that will shape the evolution of S&T over the coming decades. Natural language processing (NLP) techniques identified a set of 10 core emerging S&T trends:

- Robotics, artificial intelligence (AI), and automation
- Advanced materials and manufacturing
- Biomedical science and human augmentation
- Technologies for food and water security
- Synthetic biology
- Technologies for Improving the resilience of cities
- Cybersecurity, and technologies related to digital privacy and trust
- "Digital reality" technologies, Including mixed reality and the rise of "deepfakes"
- Energy production, harvesting, storage, and distribution
- Quantum computing

In addition to examining S&T trends, this report identifies four "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: the growth of dense urban environments, the increasing threat of resource constraints, the shifting landscape of global innovation, and the growing complexity of cybersecurity and protection in the "digital commons". The major take-aways from these contextual factors are 1) that the U.S. Army is likely to find itself operating in and around dense urban environments, 2) many future conflicts are likely to arise over limited natural resources (food, water, fossil fuels, raw materials for advanced industrial and energy applications), 3) the United States is highly unlikely to maintain its dominance in global innovation, and 4) cybersecurity will become an increasingly strong driver of R&D as more private and public sector activity moves online.

New to this year's report is an extensive analysis of global R&D and investment activity related to each S&T trend. Specifically, the report analyzed global trends in scientific publications, patent grants, and venture capital investments. The purpose of this analysis was to identify which nations and institutions are leading the way in the global research and development landscape. This data paints a deeper picture of innovation trends and highlights areas where U.S. dominance of technological dominance is potentially receding as innovation diffuses across an increasingly globalized R&D environment.

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 recent developments that signal how each trend might evolve, and visualizations of international leadership trends in research and development activity. 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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INTRODUCTION

This is the fifth edition of the Science and Technology Emerging Trends report, published annually by the office of 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 Futures and Concepts Center (FCC).

This year's report comes at a time of significant change for the Army. In July of this year, the Army stood up its Futures Command in Austin, Texas. Futures Command reflects a culminating point in the service's evolution from a force focused on the "50-meter targets" of wartime operations in Afghanistan and Iraq to a more forward-looking organization determined to harness science, technology, and other elements of strategic advantage against current and emerging threats. As an Army Command (ACOM), led by a four-star General Officer, Futures Command will have a wide reach and broad latitude to shape how the Army prepares for future conflicts, including how the service shapes its investments in new capabilities. Specifically, the Command is tasked with focusing on six innovation priorities laid out by the Chief of Staff of the Army (CSA): long-range precision fires, air/missile defense, the next-generation combat vehicle, future vertical lift platforms, expeditionary mobile networks, and Soldier lethality[1].

In a parallel vein, the Secretary of Defense has chartered a sweeping review of small unit performance through the Close Combat Lethality Task Force (CCLTF). The CCLTF is a join-service effort to "develop, evaluate, recommend, and implement improvements to U.S. squad-level infantry combat formations in order to ensure close combat overmatch against pacing threats and strengthen the combat, lethality, survivability, resiliency, and readiness of infantry squad[2]". The Army is moving out rapidly to test recommendations coming out of the task force. A pilot program is underway to evaluate the impacts of extending infantry one station unit training (OSUT), giving trainees significantly more time to focus on marksmanship, land navigation, and field training exercises[3]. The CCLTF is also considering more fundamental changes to how the Army recruits, trains, and equips small unit Soldiers[4]. Some of the task force's recommendations follow prevailing trends, such as equipping squads withaditional sensors and unmanned systems. Other ideas will be controversial, such as recruiting Soldiers into the infantry after they have completed at least one tour in a non-close combat role (e.g., as a medic, radio operator, etc.). Regardless of which CCLTF recommendations get implemented, the very fact that DoD is sponsoring such a fundamental rethink of the infantry underscores the fact that times are changing, and the Army will almost certainly change with them.

The CSA's modernization priorities and the work of the CCLTF both reflect an appreciation that the global security environment is undergoing the most rapid change since the end of the Cold War. The Army remains engaged in a global counterterrorism mission that will likely remain in place well into the future. At the same time, the force is transitioning to face a renewed era of threats from near-peer adversaries armed with capabilities that approach, and may in some cases exceed, our own[5]. The makeup of the Army will continue to evolve. For example, in 2016, DoD lifted gender restrictions on women serving in combat roles, and several women have graduated from Ranger school since the ban was lifted. It is almost certain that the share of females in front-line combat units will increase over the coming years. This will expand the

1 https://www.army.mil/standto/2018-06-06

2 http://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dtm/DTM-18-001.pdf

3 https://www.armytimes.com/news/your-army/2018/06/26/will-longer-basic-training-make-stronger-infantrymen-the-army-is-adding-8-weeks-to-osut-to-find-out/

4 https://breakingdefense.com/2018/03/top-gun-for-grunts-mattis-may-revolutionize-infantry/

5 https://www.abc.net.au/news/2019-01-02/chinese-warship-with-electromagnetic-railguns-spotted-at-sea/10680108

recruiting pool at the tip of the spear at a time when the Army is falling short of its recruiting goals[6]. Downward pressure on recruiting is a function of many factors. Some of these factors, such as cyclic changes in the job market, are likely to ebb and flow over the coming decades. Other factors, such as rising rates of obesity, are likely to exert a more enduring influence on how the Army fills critical personnel needs. These factors could have an important influence on Army technology investments, as artificial intelligence and autonomous systems step in to fill roles that currently require human Soldiers[7].

While it is impossible to accurately predict the full course of future events, it is near-certain that technology will remain a pillar of U.S. defense strategy. The United States accounts for 54% of worldwide investment in defense research and development (R&D)[8], spending $13.2 billion on basic and applied research[9] in 2018 alone[10]. Army funding of basic and applied research has grown 153% over the past 20 years, from $946 million in 1999 (in current dollars) to just over $2.39 billion in 2018[11]. Applied research and development represent the greatest share of Army S&T investment, 37% and 45%, respectively. However, basic research has posted the fastest rate of growth, indicating a significant commitment to foundational science for future innovations. With this funding, the Army maintains a world-class system of in-house research and development centers and funds hundreds of millions of dollars in extramural S&T with industry and academic partners. Sustained support for S&T is unlikely to change in the foreseeable future.

However, despite its commitment to S&T as a key enabler of new capabilities, the Army cannot assume it will maintain the overwhelming technological dominance it has enjoyed over previous decades. Emerging competitors are investing heavily in their own military modernization efforts and making sizeable technology investments of their own. China and Russia are engaged in modernization efforts that include new investments in both procurement of near-term capabilities and development of future systems. Although it is difficult to put precise numbers on Chinese and Russian defense R&D[12], both countries are increasing their overall defense expenditures. Over the 20-year period from 1998 to 2017 (the latest year for which good data are available[13]), China's defense budget has grown from $31 billion to almost $230 billion – a remarkable 642% increase. Russia's defense budget has grown from $13.6 billion to $55.3 billion, a more modest growth of 307% compared to the Chinese, but still significant. By comparison, the U.S. defense budget, while currently dwarfing both nations combined, grew a relatively "modest" 48% over the same twenty-year period.

Furthermore, while the U.S. typically spends around 3.7% of its gross domestic product (GDP) on defense, the Chinese have fueled a significant increase in defense spending while maintaining military spending at approximately 1.9% of GDP. Based on 2017 figures[14], if the Chinese had invested a similar percentage of their GDP in defense as the U.S., their spending would have been over $444 billion against a U.S. budget of approximately $597 billion. That is still a significant gap, but one that would be relatively easy for the Chinese to close given that their economy has grown at an average rate of over 9% per year compared to a 2.2% growth rate for the United States. The implication is that China likely has more budget ceiling to absorb rapid increases in defense spending than does the United States. As many defense experts have noted, the ability of the United States to rapidly ramp up its defense spending will likely be hampered as non-discretionary expenses such as interest on the national debt consume a larger share of the budget[15]. Russian defense budgets have averaged 2.9% of

6 The Army fell about 8.5% short of its recruiting goal for 2018. https://www.stripes.com/news/army/army-misses-2018-recruiting-goal-which-hasn-t-happened-since-2005-1.548580

7 Congressional Research Service (2018). U.S. Ground Forces Robotics and Autonomous Systems (RAS) and Artificial Intelligence (AI): Considerations for Congress. Retrieved from: https://fas.org/sgp/crs/weapons/R45392.pdf.

8 https://www.strategyand.pwc.com/trend/2018-defense

9 Budget categories 6.1, 6.2, and 6.3.

10 https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2018/November2017Amended/fy2018_r1a.pdf

11 Based on data from DoD R-1 reports and consumer price index data from the U.S. Bureau of Labor Statistics.

12 See https://chinapower.csis.org/military-spending/ from the Center for Strategic and International Studies (CSIS) for a good overview of the challenges associated with estimating Chinese defense spending. Many of the same challenges apply to Russia.

13 All calculations are based on data from the 2018 Stockholm International Peace Research Institute (SIPRI) database, available from https://www.sipri.org/databases/milex using 2016 constant dollars.

14 GDP data from the World Bank (https://data.worldbank.org/indicator/NY.GDP.MKTP.CD)

15 https://thehill.com/policy/finance/373647-intelligence-chief-federal-debt-is-dire-threat-to-national-security

GDP from 1998 to 2017 but have jumped to 4% over the past three years, another indicator of their modernization ambitions.

What are these funding increases buying the Chinese and the Russians? What new capabilities might both nations field over the next 30 years? While the details of these investments are classified, open source information paints a broad picture of modernization strategies aimed at challenging U.S. power projection capabilities across the globe. China and Russia are both investing heavily in anti-access/area-denial (A2AD) capabilities, including integrated air defense systems (IADS) to counter U.S. air superiority. China is aggressively pursuing naval, air, and missile systems designed to limit U.S. freedom of maneuver in the Pacific Ocean. This includes significant research and development of land attack and anti-ship ballistic missile systems, ship-based cruise missiles, undersea sensors and anti-submarine capabilities. China is also upgrading its long-range radar, jamming, anti-satellite, and cyber capabilities to counter U.S. communications and sensor networks. Chinese modernization efforts also emphasize the use of unmanned systems for strike and intelligence, surveillance, and reconnaissance (ISR) missions.

Ground forces appear to play a smaller role in Chinese military thinking. The size of the People's Liberation Army (PLA) Ground Force has been slashed over the past several years, while the Air Force, Navy, Rocket Force, and Strategic Support Force have all grown. Emphasis appears to have shifted toward smaller, more agile, ground forces with better training, leadership, and equipment. This "quality over quantity" strategy can be seen in research and development efforts such as the recent demonstration of a powered infantry exoskeleton by Chinese armored vehicle manufacturer Norinco. The exoskeleton enables troops to carry up to 100 pounds of equipment at a 5:1 rate of energy expenditure – so that 100-pound load would only require 20 pounds-worth of effort. Norinco has not publicized details on operational range, but the first-generation model tested last year ran for up to 12 hours at a walking speed of 2.8 miles per hour[16].

Russian modernization efforts place a greater emphasis on ground forces than the Chinese strategy. While the Soviet approach of quantity over quality still holds sway, the Russians are also trending toward focusing combat power in more agile, better trained, and better equipped forces. Russia's GPV 2027 modernization strategy targets $306 billion in new procurement and R&D efforts over the next decade[17]. A quarter of this funding is earmarked for ground force modernization, including automated tactical command and control systems, modern ISR, electronic warfare capabilities, and upgrades to current-generation tanks and armored vehicles. Russia is putting special emphasis on upgrading its artillery and land-attack rocket forces, with a goal of denying freedom of maneuver to U.S. and NATO forces that have come to rely on tactical mobility under the cover of assured air dominance. Unmanned systems are an important part of Russia's long-term materiel development strategy. Although unmanned systems like the Uran-9 currently fall short of advertised capabilities[18], Russia is rapidly strengthening its robotics R&D and industrial base.

It is impossible to predict with certainty how Chinese and Russian modernization efforts will turn out. Research and development are fraught with challenges and unforeseen setbacks whether one is in Beijing, Moscow, or Washington, DC. However, the days of assured American dominance of the technological landscape are most certainly numbered. As other nations seek to leverage emerging scientific and technological breakthroughs for their own purposes, it will become increasingly important for the U.S. Army to say abreast of emerging S&T trends. Technology reconnaissance and horizon-scanning efforts are likely to play a growing role in informing Army strategy.

In that spirit, the purpose of this report is to provide Army leaders and stakeholders with a broad survey of emerging science and technology trends that are likely to impact Army operations over the next 30 years. As with

16 https://www.popsci.com/china-exoskeleton-next-generation#page-4

17 Boston, S. & Massicot, D. (2017). The Russian way of war: A primer. RAND report. Available from https://www.rand.org/pubs/perspectives/PE231.html.

18 The Uran-9 is an unmanned ground vehicle that the Russians touted as being capable of operating semi-autonomously in teams of four vehicles. However, despite impressive demonstrations under controlled conditions, the Uran-9 underperformed significantly in actual combat conditions during its first deployment to Syria. Among other deficiencies, the Uran-9 experienced multiple cases of loss of control, problems with vehicle suspension, failures in ISR sensors, and unstable operation of the UGV's 30mm main gun that limited it to firing while stationary, greatly limiting the platform's combat mobility and survivability. https://www.realcleardefense.com/articles/2018/06/26/russian_ground_battlefield_robots_a_candid_evaluation_113558.html

prior editions of this report, the overall approach was to conduct a "meta-analysis" of horizon scans published by U.S. and international government agencies, industry leaders, think tanks, and other organizations that maintain a close eye on S&T trends. The trend analyses published by these organizations provide a rich set of data for mining trends that have significant potential for impacting the Army operations and materiel capabilities. Therefore, the approach adopted in this report is to synthesize the collective insights of the global foresight community and identify trends that are highly likely impact the U.S. Army over the coming decades. A total of 48 reports were included in this review 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.
- 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.

The analysis process began by compiling a database of all the trends discussed in these reports. This database included both science and technology-related trends and broader "contextual" trends that could shape the S&T landscape over the coming years. An example of a contextual trend discussed in many of the reports was accelerating urbanization, which has implications for transportation, food and water security, infrastructure resilience, and other domains where science and technology is likely to play an important role. The report review process captured over 480 science and technology trends and over 120 contextual trends. Natural language processing (NLP) techniques were then applied to identify a core set of emerging S&T and contextual trends. That analysis yielded ten S&T trends that are highly likely to impact the Army over the next 30 years, and four major contextual trends that are likely to shape the global environment for innovation:

S&T Trends

- AI, robotics, and autonomous systems
- Advanced materials and manufacturing
- Biomedical science and human augmentation
- Food and water security
- Synthetic biology
- Resilient cities
- Cybersecurity, privacy, and trust
- Digital reality
- Energy
- Quantum Computing

Contextual Trends

- Dense urban environments
- Resource constraints
- Shifting innovation landscape
- Cybersecurity and the digital commons

New to this year's report is an extensive analysis of global R&D and investment activity related to each S&T trend. The purpose of this analysis was to identify which nations and institutions are leading the way in scientific productivity, patent filings, and venture capital investment. Specifically, we analyzed three primary data sources:

- Worldwide publications in peer-reviewed scientific journals and conference proceedings indexed in the Scopus database, produced by Elsevier.
- Priority patents granted by the United States Patent and Trademark Office (USPTO), European Patent Office (EPO), Japanese Patent Office (JPO), and World Intellectual Property Organization (WIPO), as indexed in the Derwent Innovation database produced by Clarivate, supplemented with data from the PATSTAT database published by the EPO[19].
- Data on international venture capital (VC) deals over

19 A priority patent is the first patent that covers a particular innovation. Our

the past five years, published in the Crunchbase VC database.

This data paints a deeper picture of the R&E landscape and highlights areas where U.S. dominance of technological innovation is potentially receding as innovation diffuses across an increasingly globalized R&D environment. A full list of the sources included in this analysis can be found in Appendix A, and details on the analysis methodology can be found in Appendix B.

The remainder of this report is divided into two parts. First, we present the ten science and technology trends that were identified through the synthesis of open source forecasts. Appendix C provides a set of "trend cards" that give a synopsis of key information for each trend, including recent developments that signal how each trend might evolve over the coming decades along with quantitative analysis of global S&T leadership, patent activity, and venture capital investments. Following a discussion of the S&T trends, we review the four contextual trends that emerged from the meta-analysis of open-source foresight reports. The report ends with a review of key insights and recommendations for the U.S. Army.

analysis focused on priority patent grants versus applications, because grants represent a more stringent standard for identifying legitimate innovation. Anyone with enough time and money can apply for a patent, but a grant means that patent examiners deem an innovation as sufficiently distinct to warrant legal protection. We focused on grants from the USPTO, EPO, JPO, and WIPO as these offices have traditionally represented the "gold standard" for rigor in determining whether an application reflects original intellectual property. Including other offices could have biased the analysis. For example, the Chinese government strongly encourages domestic companies to file patents with the China National Intellectual Property Administration (CNIPA). CNIPA has relatively lenient standards for granting patents to Chinese organizations compared with other international patent offices. Therefore, including CNIPA grants in an analysis could significantly inflate the apparent leadership role of Chinese companies compared with those in other nations. Focusing on USPTO, EPO, JPO, and WIPO grants therefore gives a consistent baseline that reduces bias from variability in the patent review process across national patent offices.

Analysis of open-source foresight data suggests that the following 10 trends will have a significant impact on future Army capabilities and the future operating environment:

AI, Robotics, and Autonomous Systems

AI and robotics technologies have accelerated rapidly over the past five years. A recent study by the McKinsey Global Initiative found that computer vision, natural language processing, robotics, and machine learning could add $13 trillion to global GDP by 2030[20]. These technologies are already being applied in agriculture, financial services, customer support, logistics, manufacturing, and numerous other markets. In addition, global military spending on robotics and AI hit $39.2 billion in 2018 and is projected to top $60 billion by 2027[21], underscoring the growing use of AI and autonomous systems within the global defense market. Basic and applied research is accelerating in this technology space, with the number of publications in peer-reviewed journals growing from 44,806 papers in 2014 to approximately 56,000 in 2018. Notably, 2018 marks the first year that Chinese scientists published more papers related to AI and autonomous systems than U.S.-based researchers, suggesting that China's significant investments in AI/autonomy research are beginning to bear fruit. The United States does remain the world leader in patent filings, with over 5,500 patents filed by U.S.-based inventors in 2018 alone. However, China is also gaining ground in patent activity, passing Japan in 2018 to become the second-highest nation in filings. Though China remains well behind the U.S. in patenting AI and autonomous systems technologies (with 1,714 patents in 2018), the data suggest that China's dominance in the basic and applied research domain will likely translate to a rapid increase in global patents for new innovations. The rise of China as a global player in AI and autonomous systems is also reflected in venture capital flows – Chinese companies scored four of the five largest VC deals in 2018.

The U.S. Army was an early adopter of military robotics and has a broad portfolio of both fielded robotics systems and R&D efforts spanning basic and applied research. Over the next 30 years, it is likely that the Army will make greater user of robotics and autonomous systems. Advances in manned-unmanned teaming and gesture/voice communications will enable robots to operate alongside Soldiers with greater autonomy. Soldiers in the future will likely have access to a suite of robotic platforms for ISR and strike missions. In addition, the Army is exploring new applications of artificial intelligence and machine learning technologies across the range of warfighting functions. While many of these efforts are at an earlier stage of development, it is highly likely that AI will be embedded in many Army systems.

While AI and autonomous systems have demonstrated tremendous potential across multiple markets and economic sectors, this trend also poses significant potential threats for global security in general, and the U.S. Army in particular. Numerous articles have been written in the popular press about the potential displacement of workers by robots and AI. A widely-publicized study by researchers at Oxford and Yale universities surveyed over 350 of the world's leading experts on AI[22]. The authors of this paper projected a 50% chance that AI platforms would surpass human performance on most of the tasks they reviewed by the year 2050. Those most at risk include commercial vehicle drivers, factory workers, and service sector employees. For example, the automation of customer service has the potential to eliminate millions of jobs in call centers across much of the developing world[23]. Governments are beginning to grapple with the implications of AI and robotics for economic disruption. However, with the scope of the problem unclear and the commercial potential so high, few countries are making meaningful moves towards regulating AI and robotics technologies. Of course, it is entirely possible that the AI and robotics revolution will create just as many new jobs as they destroy, and many of these jobs might be higher-paying than the ones they replace (e.g., coding, robot maintenance, IT). However, rapid automation could cause significant near- and mid-term disruption while the global economy adapts, especially in regions of the world that are

20 McKinsey Global Institute (September, 2018). Notes from the AI frontier: Modeling the impact of AI on the world economy.

21 Research and Markets (January, 2018). Global artificial intelligence & robotics for defense: Market & technology forecast to 2027.

22 Grace, K., Salvatier, J., Dafoe, A., Zhang, B., & Evans, O. (2018). When will AI exceed human performance? Evidence from AI experts. Journal of Artificial Intelligence Research, 62, 729-754.

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

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[24]. 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

Materials and manufacturing science are at the heart of technologies ranging from sodium-ion batteries to 3D-printed buildings. Nanomaterials are now found in over 1,600 consumer products[25], with the global market projected to top $98 billion by 2025[26]. In addition to nanomaterials, novel ceramics and metal alloys being developed for applications ranging from airframes to battery electrodes. By 2048, advances in materials production should make many novel materials viable for commercial applications in flexible electronics, body armor, tissue engineering, and other applications. On the manufacturing side of the equation, additive manufacturing is now an established technology, widely used for both industrial production by a growing number of home hobbyists. Overall, advanced materials and manufacturing is a thriving area of research and development. Scientific publication related to this trend have grown from over 244,000 per year in 2014 to almost 300,000 per year in 2018. China has a significant lead in materials and manufacturing publications, producing more than double the number of papers in 2018 than the United States. China's dominance in this space reflects a national strategy of investment in materials research, especially related to solar cells and battery technologies.

The United States and Japan lead the way in materials and manufacturing patents, though filings by inventors in both countries have been declining over the past five years. For example, U.S. inventors filed over 25,000 materials and manufacturing-related patents in 2014, but only 13,371 in 2018. This aligns with a broader decline in priority patent filings in the United States. The number of priority patents filed with the USPTO declined in 2015 and 2017 and appear to be on track for additional declines in 2018[27]. At the same time, worldwide filings with international patent offices have been increasing. There are multiple drivers of this relative decline in U.S. patent filings, including a shift by U.S. technology firms toward emphasizing patent quality over quantity and increased reliance on trade secrets as a method for protecting intellectual property versus patents, which have become rich targets for "patent trolls" and IP thieves.

Biomedical Science and Human Augmentation

Advances in medical science are driving innovations that will optimize, and ultimately augment, human performance. This is a broad field, with key technologies including pharmacogenetics, AI-powered diagnostics, somatic gene surgery, regenerative medicine, wearable health monitors, and prosthetics integrated with the nervous system. The market for medical technologies is massive, with a projected value of $2 trillion by 2025 on strong year-over-year growth. Much of this growth will likely come from startups funded by venture capital, which stood at $50.3 billion in 2018 alone. Much of this funding went toward pharmaceutical companies using genomics to engineer new treatments for a range of life-threatening illnesses ranging from Alzheimer's disease to diabetes. VCs also backed developers of mixed, virtual, and augmented reality medical applications. There is an interesting

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

25 Vance, M. E., et al. (2015) **Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory**. *Beilstein Journal of Nanotechnology*, 6, 1769-1780.

26 https://www.reuters.com/brandfeatures/venture-capital/article?id=65231

27 https://www.ipwatchdog.com/2018/04/11/fewer-patent-applications-filed/id=94436/

contrast between growth in private equity investment in commercializing biomedical innovations on the one hand, and a decline in scientific publications in this field. Publications in key biomedical journals fell by 7% from 2014 to 2018, from almost 499,000 to just over 465,000. This could reflect a shift in the center of innovation from universities to startups and other commercial enterprises. Overall patent activity in biomedical science also suggests a shift toward a globalized innovation market. Filings by U.S.-based organizations fell by 46% from 2014 to 2018 while filings by inventors in China have risen by 13%.

Many medical innovations will have Army applications in battlefield medicine, injury prevention, and physical/cognitive performance enhancement.

Food and Water Security

Food and water security are projected to become significant sources of conflict in coming decades across much of the world. A recent study[28] by agronomists at Penn State University found that global food production will need to increase by 25% to 70% to meet global demand by 2050. United Nations data further suggests that two-thirds of people may face water shortages by 2025. Food and water are essential for life and civilization, and significant disruptions in the supply of either would almost certainly lead to a rise in regional disorder, cross-border conflict, and other forms of upheaval. Innovations such as precision agriculture, graywater recycling, vertical farming, so-called "clean meat" grown in laboratory cultures, and water-from-air could be the key to ensuring food and water security for future populations. Research in these and other areas is accelerating – scientific publications related to food and water security technologies rose 25% from 2014 to 2018, from 57,892 articles in 2014 to 72,666 articles in 2018. This increase in scientific output aligns with growth in venture capital investment in early-stage food and water security companies. VC activity in this sector was $4.2 billion in 2018, with compound annual growth of 52% from 2014. Patent activity in this technology space is less dynamic. The United States has a significant lead over Germany, China, Japan, and other nations, but U.S. patents related to food and water security have fallen sharply over the past five years – from 3,895 priority filings by U.S.-based inventors in 2014 to just 1,958 in 2018. As noted above, this data is consistent with broader declines in patent filings across multiple technology categories.

Synthetic Biology

Synthetic biology applies engineering principles to biology, using gene synthesis to create proteins and other biological structures not found in nature. Applications include biopharmaceuticals, synthetic fuel production, and converting waste to useful chemical products. The technology is evolving rapidly, driven by almost $3 billion in venture investment in 2018 alone. This is a more niche area of science and technology compared to several of the other trends reviewed in this report – there were just over 6,208 peer-reviewed publications related to synthetic biology in 2018, and the field is growing at approximately 1.4% per year. The United States leads the world in synthetic biology publications, followed by China, Germany, the United Kingdom, and Japan. Patent activity in this field is light – U.S.-based inventors filed only 165 synthetic biology patents in 2018, down 45% from 2014. The next most-prolific nation was China, with 48 patents in 2018. Most worldwide patents went to university researchers and small biopharmaceutical companies.

Biomaterials could provide the Army with new sources of fuel and life-saving medicines. However, the rapidly decreasing cost of gene synthesis also opens the door to engineered viruses and other potentially harmful biological agents.

Resilient Cities

By 2050, 6.7 billion people - 68% of the world's population - are expected to live in urban areas[29]. The surge in urbanization will exacerbate challenges related to housing, water access, waste management, transportation, information, and communication. In addition, many of the fastest-growing cities in the world are situated near coastlines, exposing residents to threats related to

28 Mitchell C. Hunter, Richard G. Smith, Meagan E. Schipanski, Lesley W. Atwood, David A. Mortensen; Agriculture in 2050: Recalibrating Targets for Sustainable Intensification, *BioScience*, Volume 67, Issue 4, 1 April 2017, Pages 386–391, https://doi.org/10.1093/biosci/bix010

29 https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

climate change such as flooding, storm surges, and other natural disasters. Making cities resilient in the face of growing populations and a changing climate will require a broad range of technological and policy interventions. On the technology front, rooftop solar and urban wind farms, autonomous public transportation systems, and networked sensors will become essential parts of daily life in tomorrow's megacities. Research related to resilient cities has grown 44% from 2014 to 2018, with the number of peer-reviewed publication rising from 27,834 to 40,109. This only counts work directly related to "smart city" technologies. It is likely that urban resilience will also benefit from leveraging broader trends in AI and robotic systems, food and water security, cyber security, and medical technology. Most urban resilience technologies are highly capital-intensive and within the purview of government agencies. Therefore, the amount of venture capital flowing into resilient city technology is relatively low - $8.6 billion in 2018. But this area is growing quickly, with investments increasing at a compound annual growth rate of 88% over the past five years. Patent activity in this area is relatively light and has been led by South Korean inventors working primarily on Internet of Things (IoT) applications such as infrastructure sensors, traffic control, and public safety.

Cybersecurity, Privacy, and Trust

2018 brought numerous front-page stories about abuse of personal data by social media companies, ongoing cyberattacks compromising personal and financial information, and growing concerns about the rise of a global surveillance state. While it is too early to tell whether public awareness of these issues will translate to widespread change, it is likely that growing levels of digital literacy among younger populations, coupled with continued migration of vital data to the Internet will fuel a greater interest in cybersecurity and privacy technologies. In particular, it is likely that new forms of "cyber camouflage" will emerge that empower individuals and organizations to protect their data and identities from governments, corporate marketers, and malicious actors. This is increasingly attractive market for venture capital, with $8 billion in investment in 2018 and compound annual growth of 62% since 2014. There is also significant basic and applied research happening in this area. Publications related to cybersecurity and digital privacy have risen 32% over the past five years, from 21,619 papers in 2014 to 28,470 papers in 2018. Notably, most of this work is being produced by Chinese scientists – Chinese authors accounted for 24% of all cybersecurity publications in 2018, followed by the United States at 19%. India, the United Kingdom, and Germany are smaller, but influential contributors to the global cybersecurity landscape. The United States maintains a significant lead in cybersecurity patents, with U.S.-based inventors filing 7,923 patents in 2018 – more than 4.5 times the number filed by the second-place patent holder, China.

Many of these technologies could find dual-use in the Army, especially in the special operations community. At the same time, technologies such as "adversarial objects" could defeat Army surveillance systems.

Digital Reality

Mixed reality blends virtual and augmented reality, creating environments in which physical and virtual objects co-exist. The technology has wide-ranging applications in immersive entertainment, training, medical care, design, and many other fields. Mixed reality is a booming business, with $5.6 billion in venture capital investments in 2018, growing at a compound annual growth rate of 82%. This is also a rapidly growing area of scientific research. Worldwide, publications related to mixed, augmented, and virtual reality are up 32% in the past five years, with 13,114 papers in 2018 alone. The United States leads mixed reality research, followed closely by China, Germany, the United Kingdom, and Japan. The United States is also the world leader in priority patent filings, with U.S. inventors filing 1,838 patents in 2018.

Digital mimicry is an emerging family of technologies that can create hyper-realistic computer-generated models of individuals. This can include still images, but more recent breakthroughs focus on manufacturing video and voice simulacra. Often referred to as "deepfakes" – a portmanteau of "deep-learning" and "fake" – this technology uses generative adversarial neural networks (GANs) combines and superimposes multiple video and voice samples of an individual, yielding synthetic footage

that is increasingly hard to distinguish from the real thing. While the technology has obvious applications in digital entertainment, malicious actors could create "deep fakes" of world leaders, military commanders, and other key figures, sowing disinformation and compromising chains of command. The Defense Advanced Research Projects Agency (DARPA) has recognized the potential threat of deepfakes as a tool for spreading disinformation. DARPA is partnering with researchers at the University of Colorado and other universities to develop tools for detecting deepfake videos[30] – setting up a technology arms race with significant implications for global security.

Energy

The U.S. Energy Information Administration projects a 28% increase in global energy use by 2040[31]. Most estimates assume fossil fuels will remain key to meeting increased demands. However, renewable energy sources such as solar and wind are nearing broad-based cost-parity with fossil fuels. Iceland and Costa Rica already generate most of their power from renewable sources, and China is making massive investments in solar infrastructure and manufacturing. Overall, energy startups received $6.4 billion in venture capital funds. This likely reflects a relatively small share of overall capital investment in energy technologies, which are primarily driven by larger, established industry leaders, including major fossil fuel companies. Renewable energy research is driving a 52% increase in R&D activity, with the number of scientific publications related to energy technologies growing from 92,000 in 2014 to over 140,000 in 2018. While energy research is expanding, the number of patent filings related to this trend has fallen steadily over the past five years. Patent applications by U.S. inventors, for example, have fallen from 25,250 in 2014 to 12,439 in 2018. Similar declines are seen across other leading nations, including Japan, China, South Korea, and Germany. As noted above, this likely reflects broad trends in global patent activity, with a greater emphasis on patents covering more significant innovations and an increase in closely-held intellectual property.

A shift to renewables could lead to new conflicts over reserves of materials needed for batteries, solar cells, and other key systems. Declining reliance on fossil fuels could also destabilize economies in nations dependent on oil and gas exports.

Quantum Computing

Long-hyped as an emerging revolution, quantum computing has been slow to show practical applications. That has begun changing rapidly, with companies in Canada, the US, Europe, and China demonstrating quantum computers that approach what IBM has referred to as "quantum dominance" - the point at which a quantum computer exceeds the performance of any classical computer. Research in quantum computing is growing steadily, with 6,456 papers published in 2018. This represents a relatively modest 15% increase in publications since 2014. Venture capital flows are also picking up slowly – there was $2.8 billion in VC-backed financing for quantum computing companies in 2018, and venture funding is growing at a compound annual growth rate (CAGR) of 13%. Patents activity has been relatively modest. The United States leads in the number of priority applications, with 298 patents in 2018. China is making well-publicized investments in quantum computing, building a $10 billion National Laboratory for Quantum Information Science in the city of Heifei[32]. However, the number of Chinese patent applications remains relatively modest at just over 80 per year on average from 2014 to 2015.

Quantum computers could transform drug discovery, enable simulations of novel materials for batteries, and lead to impervious encryption. On the other hand, the U.S. National Academy of Sciences estimates that traditional encryption schemes could be quickly cracked by a quantum computer.

30 https://www.technologyreview.com/s/611726/the-defense-department-has-produced-the-first-tools-for-catching-deepfakes/

31 https://www.eia.gov/todayinenergy/detail.php?id=32912

32 https://www.popsci.com/chinas-launches-new-quantum-research-supercenter

The science and technology trends discussed above will be shaped by a host of social, political, economic, environmental, and security-related trends. This broader context will create new opportunities for technological applications that will both benefit and challenge U.S. Army capabilities. Within the next 30 years, four contextual trends will have an especially profound impact on defense-related S&T: the rise of dense urban environments, resource constraints, a shifting global innovation landscape, and disruptive changes in cybersecurity and the "digital commons". This section reviews each of these trends and how it might impact emerging S&T.

Dense Urban Environments

By 2047, approximately two-thirds of the world's population will live in urban areas[33]. 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[34]. 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[35]. 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.

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 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[36].

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[37], 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

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

34 Ibid.

35 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.

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

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

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[38]. 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[39], 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[40]. 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.

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 Innovation Landscape

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[41]. 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[42]. 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.

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[43]. 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.

38 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.

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

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

41 Statistic based on data from the Industrial Research Institute's annual Global R&D Funding Forecast.

42 Industrial Research Institute 2017 Global R&D Funding Forecast.

43 http://www.wipo.int/pressroom/en/articles/2016/article_0017.html

Cybersecurity and the Digital Commons

In 1988, a Cornell University graduate student named Robert Tappan Morris accidentally unleashed the world's first large-scale cyberattack. Morris wrote a program designed to measure the number of devices connected to the Internet by traveling from device to device. Each device would copy Morris' code and send it back across the network, creating an echo that tied up bandwidth and ground large part of the Internet to a halt. Within 72 hours, Morris Worm became the first distributed denial of service attack (DDoS) code, infecting 10% of Internet-connected devices and causing hundreds of thousands of dollars in recovery costs to affected users[44].

From this innocent beginning, cybersecurity has become a leading concern of governments, industry leaders, and consumers. By 2023, the global market for cybersecurity solutions is forecasted to top $248 billion, with a compound annual growth rate of 10.2%[45]. Most information technology experts believe that cybersecurity is reaching a critical inflection point as the number of Internet-connected devices skyrockets, while the barriers to entry for wide-scale cyberattacks declines. For example, by 2025, the number of Internet of Things (IoT) connected devices is expected to exceed 75 billion[46]. This will include mobile devices, wearable health technologies, sensors built into power grids and other smart infrastructure, networked autonomous vehicles, and numerous other applications. The IoT is creating a large and diverse set of new attack surfaces that will be exceedingly attractive to transnational criminal organizations and state-sanctioned cyber warriors. A global chorus of cybersecurity experts have pointed out that many IoT devices lack basic cybersecurity measures, are unable to receive security updates, and are often installed in remote or inaccessible locations that make security maintenance impractical[47].

One example of the looming threat from insecure IoT devices was the Mirai botnet attack that cut much of the U.S. east coast off from the Internet in the Fall of 2016[48]. Mirai infected tens of millions of networked closed-circuit television cameras and routers before launching a DDoS attack that took down servers belonging to Dyn Inc., a company that provides critical web infrastructure for some of the world's largest websites, including Twitter, Spotify, Reddit, and Amazon[49]. Mirai was a relatively simple botnet – it scanned large numbers of internet protocol (IP) addresses and attempted to log in using a list of 61 username/password combinations that are frequently used as defaults in IoT devices. Since these devices are difficult to update, most installer and end-users do not change the default credentials.

The risks associated with weak IoT security will become even more apparent as artificial intelligence becomes a primary tool in the cyber arsenal. Cybersecurity professionals anticipate that the future will be driven by AI vs. AI conflicts. Furthermore, AI cybercombatants will likely be capable of autonomous adaptation, mutating in near real-time in response to attempted countermeasures. The speed of AI-driven attacks will call for AI-driven defenses, with human relegated to the role of supervising cyberconflicts that will take place at nanosecond time scales. While technologies such as blockchain and universal second factor authentication might protect against certain attacks, many experts in the cybersecurity community predict that engineering resilience against inevitable intrusions will become a better strategy than preventing attacks in the first place.

A parallel trend in the digital security space is the growing debate over privacy and trust in the era of social media and other online interactions. Over the past year, consumer groups and government watchdogs in the United States and Europe have begun questioning whether companies like Facebook should be required to give users more control over how their personal data are used, shared, and sold.

44 Morris was prosecuted under the then-new Computer Fraud and Abuse Act, receiving three years of probation and a $10,000 fine. He went on to cofound one of the first eCommerce stores, which sold for $49 million in 1998. Morris is now a tenured professor at MIT. https://www.weforum.org/agenda/2018/11/30-years-ago-the-world-s-first-cyberattack-set-the-stage-for-modern-cybersecurity-challenges/

45 https://www.marketsandmarkets.com/PressReleases/cyber-security.asp

46 Alam, T. (2018). A Reliable Communication Framework and Its Use in Internet of Things (IoT). International Journal of Scientific Research in Computer Science, Engineering and Information Technology (IJSRCSEIT), ISSN, 2456-3307.

47 Hassan, W. H. (2019). Current research on Internet of Things (IoT) security: A survey. Computer Networks, 148, 283-294.

48 https://www.csoonline.com/article/3258748/the-mirai-botnet-explained-how-teen-scammers-and-cctv-cameras-almost-brought-down-the-internet.html

49 Mirai was developed by a Rutgers university undergraduate student named Para Jha and several of his friends. It was originally intended to attack servers hosting the video game Minecraft. Jha and his associated released the code on the Hackforums website, which has led to its use in numerous cyberattacks since 2016.

Revelations of systematic campaigns of disinformation and manipulation of social media by state-sponsored groups seeking to influence elections in the U.S. and Europe have accelerate a public backlash against the power of social media companies in the digital commons. While it is extremely unlikely that there will be a significant global retreat from social media platforms over the next 30 years, the groundswell of public opinion, especially in Western nations, is likely to trigger tighter regulation of social media and new technologies for protecting online identity.

CONCLUSIONS

This report presented a synthesis of 48 forecasts of emerging trends that are likely to impact the United States Army over the next 30 years. The objectives of this synthesis are to inform leaders across the U.S. Army and its stakeholders about S&T trends that are likely to shape warfighting capabilities, and 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. Over 600 individual trends were distilled from the open source reports into a core set of 10 emerging S&T trends and 4 contextual trends that will shape Army capabilities as it enters a new era marked by accelerating change.

The global security environment is entering a period of significant change not seen since the fall of the Soviet Union. The United States Army is facing a transition from fighting regional conflicts against terrorists and insurgents to preparing for multi-domain conflict with near-peer competitors. For the past 30 years, the U.S. has had the luxury of being able to invest in new technologies from a position of technical and warfighting dominance. Over the next 30 years, we will face a significantly more challenging environment.

- Robotics and autonomous systems are already a factor on the battlefield, and their presence will likely undergo rapid expansion over the next 30 years. While the U.S. and our allies grapple with the ethical limits on autonomous systems in war, many of our adversaries will likely show few qualms in fielding robots designed and empowered to kill.
- Advanced materials and manufacturing technologies will deliver breakthroughs in force protection, weapon system performance, and sustainment, but the high cost associated with producing many new materials at scale may force difficult choices in the acquisitions process.
- Biomedical science and human augmentation will have a profound impact on the health of the force and combat survivability. Troops may benefit from powered exoskeletons and cognitive enhancements, though the development of those technologies still faces significant technical and regulatory hurdles. As with autonomous systems technology, It Is likely that potential adversaries will be more willing than us to assume risk with enhancing their warfighters.
- Food and water security are likely to become major drivers of global conflict, as climate change drives down agricultural yields and causes severe drought in many already unstable regions. There are a number of emerging technologies that might Improve food and water security - the challenges will be In scaling these technologies to meet the scope of the problem and In distributing them equitably so that the technologies themselves do not become a new source of conflict.
- Synthetic biology is a cross-cutting field with the potential to Impact food and water security, energy, biomedical science, and many other domains. The ability to engineer DNA to produce functional biological organisms will likely bring innovations as profound as those that ushered in the current information age. However, synthetic biology also carries significant risk of both intentional and unintentional harm, especially given the rapidly declining cost of gene-editing technologies like CRISPR.
- Climate change and the ongoing migration of people to dense urban environments Is already shaping Investments to make cities resilient. Smart grids, autonomous transportation networks, vertical micro-farming, and other technologies will make future cities more efficient, livable, and protected against rising seas and climate extremes. Of course, many of these technologies will require significant capital investment and a reasonably sound foundation of infrastructure, public safety, and governance. That may put resilience technologies out of reach of many rapidly growing megacities In poorer parts of the world. The divide between urban haves and have-nots may be a source of instability In years to come.
- Cybersecurity is already a major concern for the U.S. Army, and new challenges are likely to emerge as artificial Intelligence leads to adaptive, autonomous malware that can evade traditional countermeasures. One particularly urgent challenge will be ensuring

that Army systems procured from commercial vendors are secure against the kind of cheap and simple exploits that plague emerging Internet of Things technologies. Recent incidents like the Mirai botnet attack lay bare the risks associated with proliferation of unsecured embedded systems.

- Mixed reality technologies that merge real and virtual worlds are likely to find applications across most warfighting functions and provide significant improvements to training. Over the next 30 years It is highly likely that mixed reality applications will gain fidelity while the encumbrance of the hardware will decrease. Much of the innovation in this space is likely to come from the commercial sector, which the Army should be able to leverage. In a parallel vein, digital mimicry technology is likely to present a growing threat, as open source tools make it increasingly easy to impersonate real people. Future mission command and communications systems will have to incorporate "assured identity" technologies to protect from deepfakes.

- Energy technologies will continue evolving over the next 30 years, with more efficient renewables and larger-capacity batteries providing new capabilities for force sustainment. At the same time, much of the commercial innovation In renewables is likely to shift to China, creating potential risks for the U.S. defense industrial base. Conflicts over resources needed for energy production - including fossil fuels - are likely to remain an ongoing trigger for Army engagement.

- Quantum computing appears to be reaching an Inflection point, with practical applications beginning to become feasible. Quantum cryptography has the potential to disrupt network security, and it is likely that the next 30 years will bring an arms race between the U.S. and near-peer competitors for supremacy in quantum encryption/decryption.

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. How can we posture the force to benefit more rapidly from technological innovation, particularly by leveraging commercial research and development efforts? How can the Army better work with foreign governments and international research and development centers to ensure that the Army has access to cutting-edge technologies developed outside the United States? How can the Army foster emerging innovators, such as start-ups, that fall outside the traditional defense R&D enterprise? 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.

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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 *Summarizing* 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 48 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.
- 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.

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 addition, we identified trends related to broader contextual forces that are likely to drive S&T innovation. In all, this review isolated 487 individual S&T trends and 123 contextual trends from the source documents. A Microsoft Excel database was created to store citation information for each document-specific trend along with page numbers and quotes to support further analysis.

Based on this data set, the next step was to cluster the data and synthesize a set of emerging S&T and contextual trends. An initial set of candidate S&T and contextual trends was developed using latent semantic analysis (LSA), a statistical approach for identifying similarities among a collection of texts[50]. 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 not 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.
5. Cluster analysis using Ward's method[51] 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

50 Landauer, T. K., Foltz, P. W., & Laham, D. (1998). Introduction to latent semantic analysis. Discourse Processes, 25, 259-284.

51 Everitt, B. S., Landau, S. and Leese, M. (2001), Cluster Analysis, 4th Edition, Oxford University Press..

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 summarization phase, described below.

The summarization phase involved qualitative analysis and adjustment of the clusters that resulted from the statistical analysis to identify a coherent set of themes. This step was essential for producing a final set of emerging trends because it compensated for known limitation of LSA. For example, LSA has difficulty handling polysemy – words that have multiple meanings. Similarly, LSA has only limited ability to detect deep structure based on contextual cues[52]. LSA is useful as a first pass for identifying potential clusters of common trends, but human judgment is still required to make sure that these clusters make sense. 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, 4 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.

R&D Landscape Analysis

New to this year's report is an extensive analysis of global R&D and investment activity related to each S&T trend. The purpose of this analysis was to identify which nations and institutions are leading the way in scientific productivity, patent filings, and venture capital investment. Specifically, we analyzed three primary data sources:

- Worldwide publications in peer-reviewed scientific journals and conference proceedings indexed in the Scopus database, produced by Elsevier.
- Priority patents granted by the United States Patent and Trademark Office (USPTO), European Patent Office (EPO), Japanese Patent Office (JPO), and World Intellectual Property Organization (WIPO), as indexed in the Derwent Innovation database produced by Clarivate, supplemented with data from the PATSTAT database published by the EPO[53].
- Data on international venture capital (VC) deals over the past five years, published in the Crunchbase VC database.

The analysis began by collecting data one each trend from each of the sources discussed above. Each database has unique capabilities and limitations for data retrieval. Therefore, our data collection strategy had to be tailored for each data source. In general, however, the process involved defining a Boolean search query for each trend based on an initial analysis of potential keywords identified in the source documents and supplemented with additional document research. Queries were run against each database according to its query interface. Scopus and Crunchbase have an application programming interfaces (API) that facilitated automatic data retrieval using custom data mining scripts that we developed using the Python programming language. Derwent has an API, but we found it simpler to use their web-based search portal for this analysis – though the API is a more promising route for ongoing horizon-scanning applications. PATSTAT is available as a user-defined SQL database that can be queried using standard database techniques. In this case, we wrote

52 We are experimenting with several newer techniques for text clustering, including the use of document embedding techniques that retain the semantic relationships within a text, e.g., Le, Q., & Mikolov, T. (2014, January). Distributed representations of sentences and documents. In International conference on machine learning (pp. 1188-1196). We anticipate implementing a new clustering approach for the next edition of this report.

53 A priority patent is the first patent that covers a particular innovation. Our analysis focused on priority patent grants versus applications, because grants represent a more stringent standard for identifying legitimate innovation. Anyone with enough time and money can apply for a patent, but a grant means that patent examiners deem an innovation as sufficiently distinct to warrant legal protection. We focused on grants from the USPTO, EPO, JPO, and WIPO as these offices have traditionally represented the "gold standard" for rigor in determining whether an application reflects original intellectual property. Including other offices could have biased the analysis. For example, the Chinese government strongly encourages domestic companies to file patents with the China National Intellectual Property Administration (CNIPA). CNIPA has relatively lenient standards for granting patents to Chinese organizations compared with other international patent offices. Therefore, including CNIPA grants in an analysis could significantly inflate the apparent leadership role of Chinese companies compared with those in other nations. Focusing on USPTO, EPO, JPO, and WIPO grants therefore gives a consistent baseline that reduces bias from variability in the patent review process across national patent offices.

custom Python scripts that queried a PostgreSQL database using PostgreSQL's built-in full-text search capabilities.

Data retrieved from these databases came in a variety of formats, including tab-delimited text, javascript object notation (JSON), and raw SQL. We developed a pre-processing pipeline that can ingest data in multiple formats and standardize it to comma-separated value (csv) format for analysis. In all cases, we were most interested in bibliometric data including the nationalities of document authors and publication year.

For purposes of this report, we were most interested in broad trends in national leadership and the identification of lead organizations associated with the greatest amount of S&T productivity. We developed additional scripts to identify, for each trend:

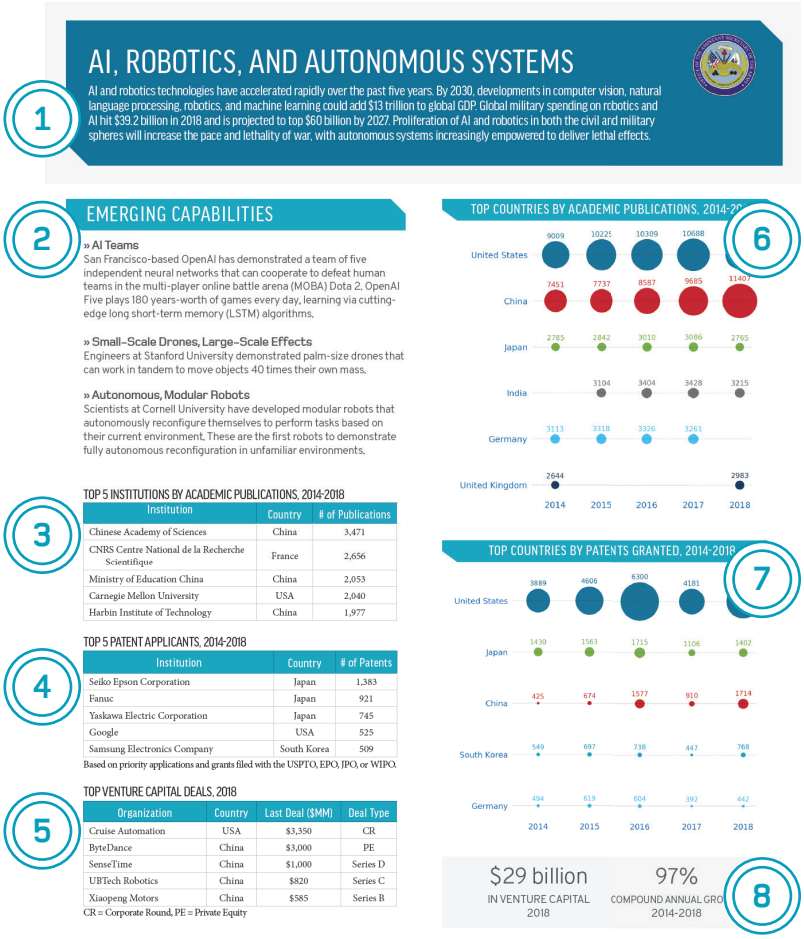
- The leading nations in terms of scientific productivity over the past five years, based on peer-reviewed publication in Scopus.
- The leading nations in terms of applied development over the past five years, based on unique patent grants by the USPTO, EPO, JPO, and WIPO indexed in Derwent Innovation and PATSTAT.
- Overall venture capital investments for each trend, and the compound annual growth rate (CAGR) over the past 5 years, based on data from Crunchbase.
- The top institutions worldwide in terms of scientific productivity over the past five years, based on peer-reviewed publication in Scopus.
- The top organizations worldwide in terms of applied development over the past five years, based on unique patent grants by the USPTO, EPO, JPO, and WIPO indexed in Derwent Innovation and PATSTAT.
- The top recipients of VC funding in 2018 based on data from Crunchbase. Our window for this analysis was limited to 2018 because of the significant volatility from year-to-year in startup viability and investment volumes.

APPENDIX C: TREND CARDS

This Appendix contains a set of "trend cards" that summarize key data for each of the 10 S&T trends discussed in this report. The cards are designed to stand alone, and they offer a concise vehicle for conveying the trends in briefings, as hand-outs, and as tools for guiding strategic dialogue.

Each card contains the following information:

1. A brief description of the trend.
2. Recent developments in research and development that signal how new capabilities might evolve over the next 30 years.
3. The top 5 institutions by total number of publications over the past 5 years in peer-reviewed academic journals and conference proceedings. From data provided by Elsevier's Scopus publication database.
4. The top 5 patent holders worldwide, based on priority patent grants from the USPTO, EPO, JPO, and WIPO over the past five years. Based on data from the Derwent Innovation and PATSTAT databases.
5. The 5 largest venture capital deals in 2018, based on data from Crunchbase.
6. Global leadership in scientific publications from 2014 through 2018, baseed on data from Scopus. In these graphs, the size of each circle corresponds to the relative number of publications (the actual value is shown above each circle).
7. Global leadership in atents from 2014 through 2018, baseed on data from Derwent Innovations and PATSTAT. In these graphs, the size of each circle corresponds to the relative number of publications (the actual value is shown above each circle).
8. The total amount of VC funding in the trend, across all sources, and the compund annual growth rate (CAGR) over the past five years.



Key to Venture Capital Investment Categories

- Series A and Series B rounds are funding rounds for earlier stage companies and range on average between $1M–$30M.
- Series C rounds and onwards are for later stage and more established companies. These rounds are usually $10M+ and are often much larger.
- Private Equity: A private equity round is led by a private equity firm or a hedge fund and is a late stage round. It is a less risky investment because the company is more firmly established, and the rounds are typically upwards of $50M.
- Grant: A grant is when a company, investor, or government agency provides capital to a company without taking an equity stake in the company.
- Corporate Round: A corporate round occurs when a company, rather than a venture capital firm, makes an investment in another company. These are often, though not necessarily, done for the purpose of forming a strategic partnership.
- Grants: corporate rounds, private equity, and VC from other unspecified sources.

AI, ROBOTICS, AND AUTONOMOUS SYSTEMS

AI and robotics technologies have accelerated rapidly over the past five years. By 2030, developments in computer vision, natural language processing, robotics, and machine learning could add $13 trillion to global GDP. Global military spending on robotics and AI hit $39.2 billion in 2018 and is projected to top $60 billion by 2027. Proliferation of AI and robotics in both the civil and military spheres will increase the pace and lethality of war, with autonomous systems increasingly empowered to deliver lethal effects.

EMERGING CAPABILITIES

» AI Teams

San Francisco-based OpenAI has demonstrated a team of five independent neural networks that can cooperate to defeat human teams in the multi-player online battle arena (MOBA) Dota 2. OpenAI Five plays 180 years-worth of games every day, learning via cutting-edge long short-term memory (LSTM) algorithms.

» Small–Scale Drones, Large–Scale Effects

Engineers at Stanford University demonstrated palm-size drones that can work in tandem to move objects 40 times their own mass.

» Autonomous, Modular Robots

Scientists at Cornell University have developed modular robots that autonomously reconfigure themselves to perform tasks based on their current environment. These are the first robots to demonstrate fully autonomous reconfiguration in unfamiliar environments.

TOP 5 INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Chinese Academy of Sciences	China	3,471
CNRS Centre National de la Recherche Scientifique	France	2,656
Ministry of Education China	China	2,053
Carnegie Mellon University	USA	2,040
Harbin Institute of Technology	China	1,977

TOP 5 PATENT APPLICANTS, 2014-2018

Institution	Country	# of Patents
Seiko Epson Corporation	Japan	1,383
Fanuc	Japan	921
Yaskawa Electric Corporation	Japan	745
Google	USA	525
Samsung Electronics Company	South Korea	509

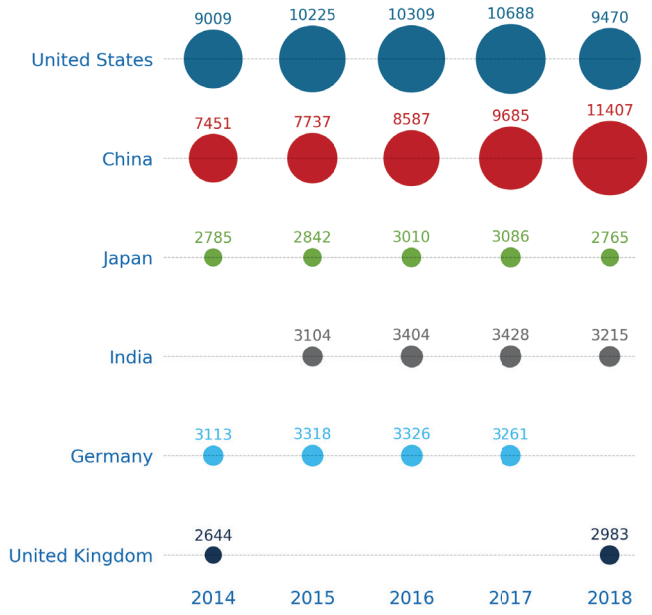
Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

TOP VENTURE CAPITAL DEALS, 2018

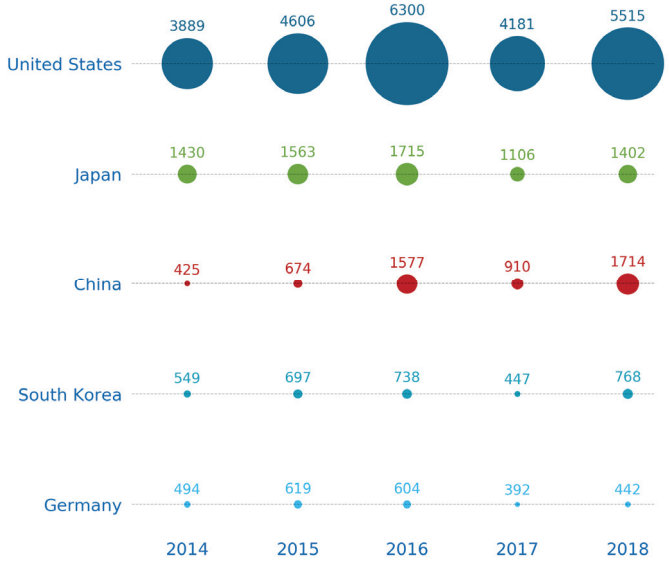
Organization	Country	Last Deal ($MM)	Deal Type
Cruise Automation	USA	$3,350	CR
ByteDance	China	$3,000	PE
SenseTime	China	$1,000	Series D
UBTech Robotics	China	$820	Series C
Xiaopeng Motors	China	$585	Series B

CR = Corporate Round, PE = Private Equity

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$29 billion
IN VENTURE CAPITAL 2018

97%
COMPOUND ANNUAL GROWTH 2014-2018

ADVANCED MATERIALS AND MANUFACTURING

Materials and manufacturing science is at the heart of technologies ranging from sodium-ion batteries to 3D-printed buildings. Nanomaterials are now found in over 1,600 consumer products, with the global market projected to top $98 billion by 2025. Additive manufacturing is now an established technology, widely used for both industrial production by a growing number of home hobbyists. By 2045, advances in production should make many novel materials viable for commercial applications in flexible electronics, body armor, tissue engineering, and other applications.

EMERGING CAPABILITIES

» Industrial–Scale Graphene

MIT engineers have developed a process for manufacturing graphene membranes at industrial scales. The process deposits methane and hydrogen gas onto heated strips of copper foil, producing graphene membrane at a rate of 5 centimeter per minute.

» Magnetic Volumetric Printing

A Slovenian inventor has filed an international patent for a 3D printer using magnetic levitation of powder materials for fast volumetric printing. Volumetric printing can create complex parts much faster than traditional layer-by-layer additive manufacturing methods.

» AI and Materials Science

Engineers at Texas A&M are using machine learning to discover new materials. Autonomous algorithms can explore a complex materials design space to find the optimal material to fit any given criteria.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Chinese Academy of Sciences	China	48,389
Ministry of Education China	China	42,080
CNRS Centre National de la Recherche Scientifique	France	19,793
Russian Academy of Sciences	Russia	16,278
University of Chinese Academy of Sciences	China	11,817

TOP PATENT HOLDERS, 2014-2018

Institution	Country	# of Patents
Lg Chem	South Korea	2,177
Fujifilm	Japan	2,008
Dow Global Technologies	USA	1,942
Basf (Badische Anilin & Soda Fabrik)	Germany	1,928
Toray Industries	Japan	1,644

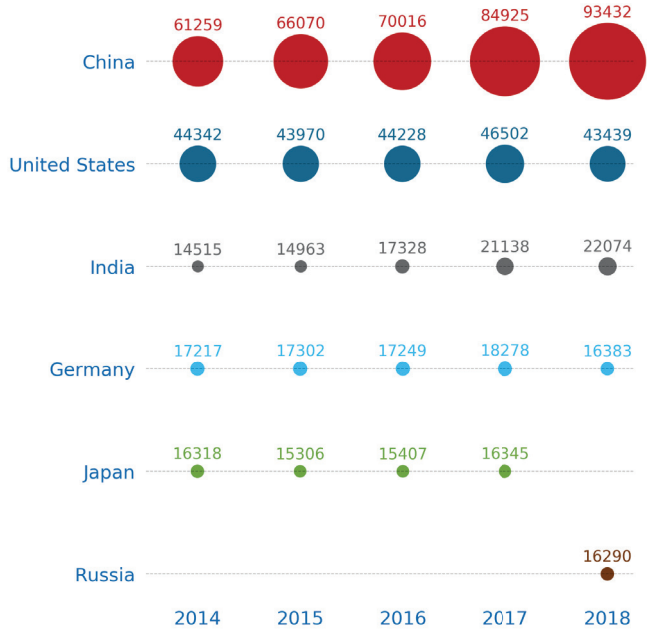
Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

TOP VENTURE CAPITAL DEALS, 2018

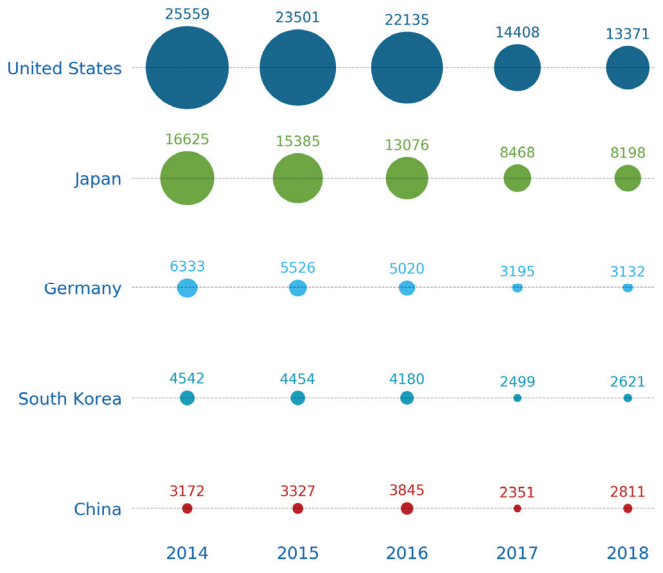
Organization	Country	Last Deal ($MM)	Deal Type
Sila Nanotechnologies	USA	$70	Series D
Apeel Sciences	USA	$70	Series C
Oxford Nanopore Technologies	UK	$65	VC
Desktop Metal	USA	$65	Series D
Ultracraft	China	$47	Series A

VC = Venture Capital (Unspecified)

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$2.4 billion
IN VENTURE CAPITAL 2018

64%
COMPOUND ANNUAL GROWTH 2014-2018

BIOMEDICAL SCIENCE AND HUMAN AUGMENTATION

Advances in medical science are driving innovations that will optimize, and ultimately augment, human performance. Key technologies include pharmacogenetics, AI-powered diagnostics, somatic gene surgery, regenerative medicine, wearable health monitors, and prosthetics integrated with the nervous system. The market for these and other medical technologies is projected to top $2 trillion by 2025. Many medical innovations will have Army applications in battlefield medicine, injury prevention, and physical/cognitive performance enhancement.

EMERGING CAPABILITIES

» Genetically–Engineered Embryos

Chinese scientist He Jiankui created the world's first genetically engineered human embryos, using CRISPR-Cas9 to impart resististance to HIV. Two twin girls were born from these embryos, shocking scientists and bioethicists around the world.

» DNA Origami

Scientists in the US and China have developed self-assembling nanodevices that can treat kidney disease. These structures, known as DNA origami nanostructures (DONs) reduce oxidative stress on kidney tissue by scavenging reactive oxygen molecules.

» Spinal Scaffolds

Researchers at University of California have used 3D printing to create a spinal cord scaffolding loaded with neural stem cells. Scaffolds were transplanted into rats with severe spinal cord injuries, leading to significant improvement in motor function.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Harvard Medical School	USA	35,490
INSERM	France	29,064
University of Toronto	Canada	26,203
VA Medical Centers	USA	25,766
University College London	UK	20,894

TOP PATENT HOLDERS, 2014-2018

Institution	Country	# of Patents
Toshiba Medical Systems Corporation	Japan	1,473
Philips Electronics	Netherlands	1,383
Medtronic	USA	1,235
Samsung Electronics Company	South Korea	1,219
Boston Scientific Scimed	USA	1,107

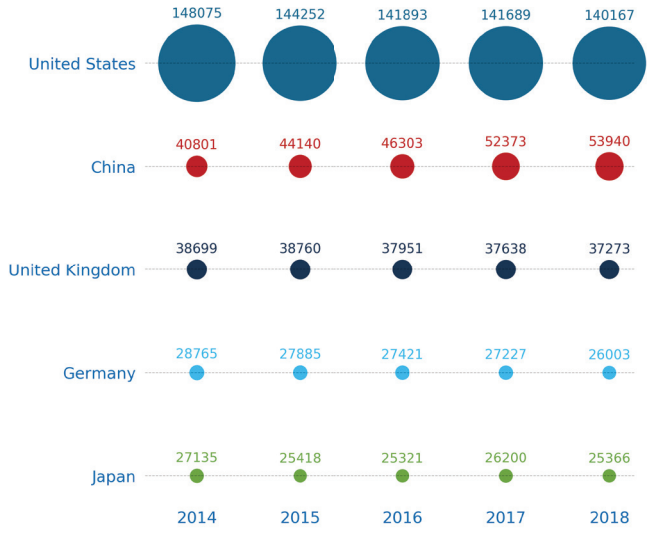
Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

TOP VENTURE CAPITAL DEALS, 2018

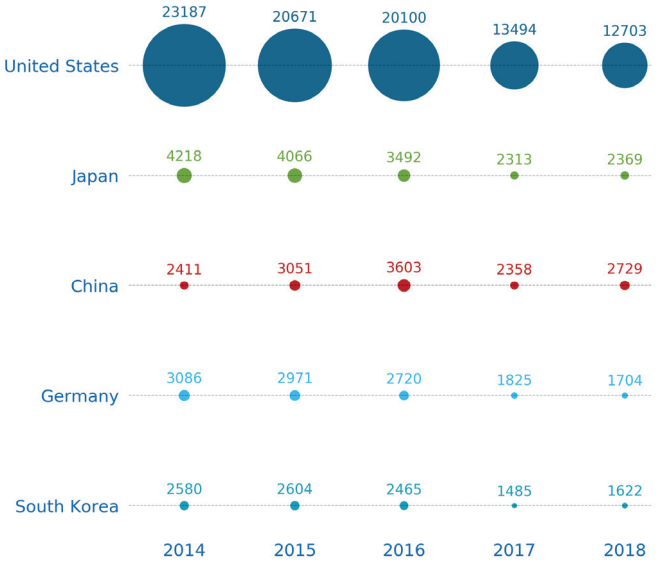
Organization	Country	Last Deal ($MM)	Deal Type
Samsung Bioepis	South Korea	$668	VC
Magic Leap	USA	$461	Series D
Samumed	USA	$438	Series A
Zymergen	USA	$400	Series C
Relay Therapeutics	USA	$400	Series C

VC = Venture Capital (Unspecified)

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$50.3 billion
IN VENTURE CAPITAL
2018

46%
COMPOUND ANNUAL GROWTH
2014-2018

FOOD AND WATER SECURITY

Food and water security are projected to become significant sources of conflict in coming decades across much of the world. The United Nations estimates the world will need to produce 70% more food by 2050 to meet global demand, and two-thirds of people may face water shortages by 2025. Innovations such as precision agriculture, graywater recycling, vertical farming, and water-from-air could be the key to avoiding civil disorder and cross-border conflicts that could quickly spiral out of control.

EMERGING CAPABILITIES

» Lab-Grown Meat

It takes 1,800 gallons of water to yield one pound of beef from traditional cattle farming. Lab-grown meat (or "cultured meat") uses tissue culturing to produce beef and other meats without relying on animal stock. Over 20 companies entered the cultured meat space in 2018. Most are headquartered in Europe.

» Water-from-Air

California-based Skysource / Skywater Alliance won the 2018 Water Abundance XPRIZE for an easily deployable high-volume water generator that can be used in any climate, extracting a minimum of 2,000 liters of water a day from the atmosphere for less than two cents per liter.

» Aeroponic Farming

UK-based LettUs Grow raised $1.3 million from investors, universities, and government funders for its irrigation and monitoring technology for aeroponic farms, which grows crops indoors without soil.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Chinese Academy of Sciences	China	13,707
Ministry of Education China	China	7,584
University of Chinese Academy of Sciences	China	4,342
CNRS Centre National de la Recherche Scientifique	France	3,309
Wageningen University and Research Centre	Netherlands	2,599

TOP PATENT HOLDERS, 2014-2018

Institution	Country	# of Patents
Cnh Industrial America	USA	768
Nestec	Switzerland	399
John Deere	USA	391
Cnh (Case New Holland) Belgium	Belgium	343
Dow Agrosciences	USA	297

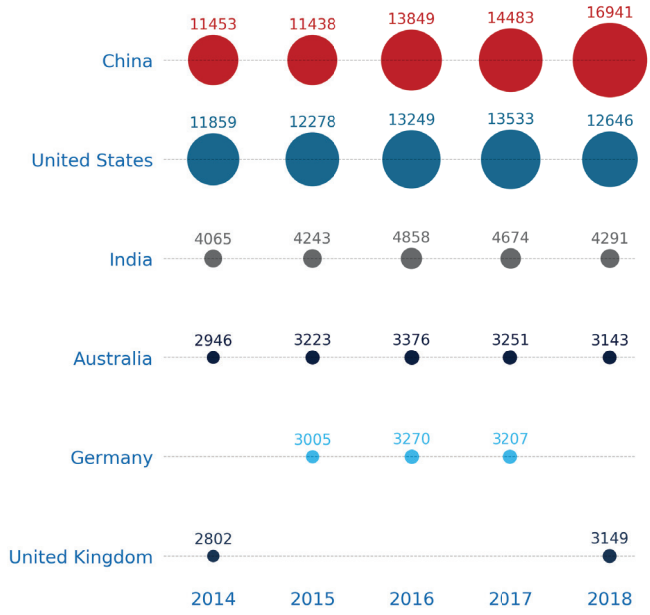
Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

TOP VENTURE CAPITAL DEALS, 2018

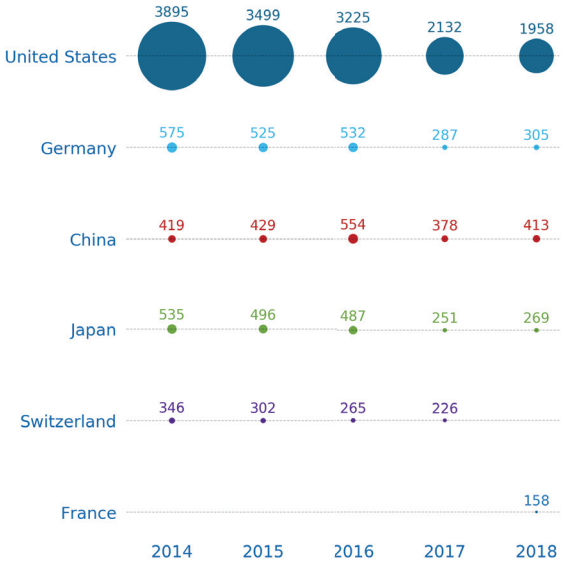
Organization	Country	Last Deal ($MM)	Deal Type
Meicai	China	$800	Series F
Indigo	USA	$250	Series E
Lionbridge Financial Leasing (China)	China	$149	CR
AgriProtein	South Africa	$105	VC
Bowery Farming	USA	$90	Series B

CR = Corporate Round, VC = Venture Capital (Unspecified)

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$4.2 billion
IN VENTURE CAPITAL 2018

52%
COMPOUND ANNUAL GROWTH 2014-2018

SYNTHETIC BIOLOGY

Synthetic biology applies engineering principles to biology, using gene synthesis to create proteins and other biological structures not found in nature. Applications include biopharmaceuticals, synthetic fuel production, and converting waste to useful chemical products. The technology is evolving rapidly, driven by almost $3 billion in venture investment in 2018 alone. Biomaterials could provide the Army with new sources of fuel and life-saving medicines. However, the rapidly decreasing cost of gene synthesis also opens the door to engineered viruses and other potentially harmful biological agents.

EMERGING CAPABILITIES

» Marine Bacteria as Sensors

The U.S. Naval Research Laboratory is investing $45 billion in a program to genetically modify common marine bacteria, turning them into sensors that can detect and track the movement of submarines.

» Asian Synthetic Biology Partnership

Singapore is investing $19 million over five years in a synthetic biology partnership with China. The initiative prioritizes developing synthetic cannabinoids, producing rare fatty acids, and developing new strains of microorganisms that can be used to create products for industry.

» Printed DNA

Ginkgo Bioworks has developed an automated process for combining genetic parts, making the Boston-based startup the largest designer of printed DNA in the world. Ginkgo's technology enables DNA to be programmed like a computer, leading to application across a wide range of industries.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Ministry of Education China	China	952
Chinese Academy of Sciences	China	939
CNRS Centre National de la Recherche Scientifique	France	541
Harvard Medical School	USA	442
MIT	USA	430

TOP PATENT HOLDERS, 2014-2018

Institution	Country	# of Patents
Cellectis	France	38
Mit (Massachusetts Institute Of Technology)	USA	38
Harvard University	USA	36
Regeneron Pharmaceuticals	USA	31
The Broad Institute	USA	24

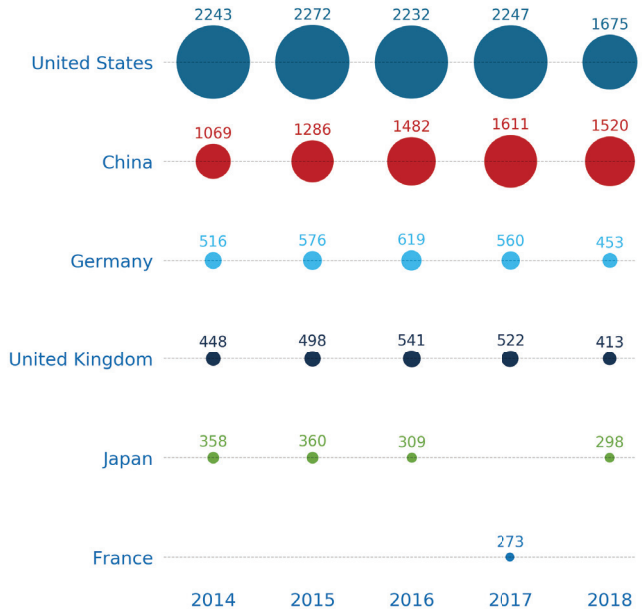
Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

TOP VENTURE CAPITAL DEALS, 2018

Organization	Country	Last Deal ($MM)	Deal Type
Zymergen	USA	$400	Series C
Moderna Therapeutics	USA	$125	Series H
Sutro Biopharma	USA	$85	Series E
Synthorx	USA	$63	Series C
Twist Bioscience	USA	$50	VC

VC = Venture Capital (Unspecified)

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018

$2.8 billion
IN VENTURE CAPITAL 2018

13%
COMPOUND ANNUAL GROWTH 2014-2018

RESILIENT CITIES

By 2050, 6.7 billion people - 68% of the world's population - are expected to live in urban areas. The surge in urbanization will exacerbate challenges related to housing, water access, waste management, transportation, information, and communication. Technology will play an important role in addressing these challenges. Rooftop solar and urban wind farms, autonomous public transportation systems, and networked sensors will become essential parts of daily life in tomorrow's megacities.

EMERGING CAPABILITIES

» Urban Cyber Resilience

The city of Rotterdam has developed the first-ever city cyber resilience strategy, emphasizing security of port-related information and communications technology.

» 5G Networking

5G is the next step in the evolution of mobile networking, offering wireless download speeds of at least 20 Gb/second – 20 times the bandwidth of current 4G networks. By 2048, it is possible that mobile bandwidth could reach 60 Gb/sec, enabling wireless transmission of massive data sets from real-time urban sensors, vehicle-to-vehicle communications systems, and public safety infrastructure.

» Sponge Cities

China is investing over $240 million to fund pilot tests of a permeable pavement material in 16 cities. The material soaks up water, diverting it to collection facilities where it can be purified and fed into the water supply. This provides fresh water and reduces the risk of flooding.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Chinese Academy of Sciences	China	2,803
Ministry of Education China	China	1,856
Tsinghua University	China	1,309
Tongji University	China	1,072
Delft University of Technology	Netherlands	1,050

TOP PATENT HOLDERS, 2014-2018

Institution	Country	# of Patents
AT&T Intellectual Property Holdings	USA	2,184
Google	USA	1.066
Samsung Electronics	South Korea	754
International Business Machines (IBM)	USA	442
Cisco Technologies, Inc.	USA	390

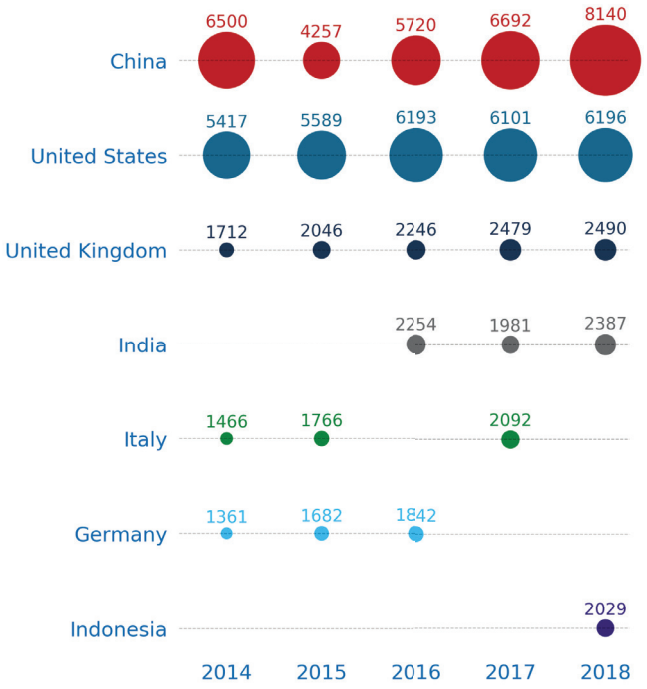
Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

TOP VENTURE CAPITAL DEALS, 2018

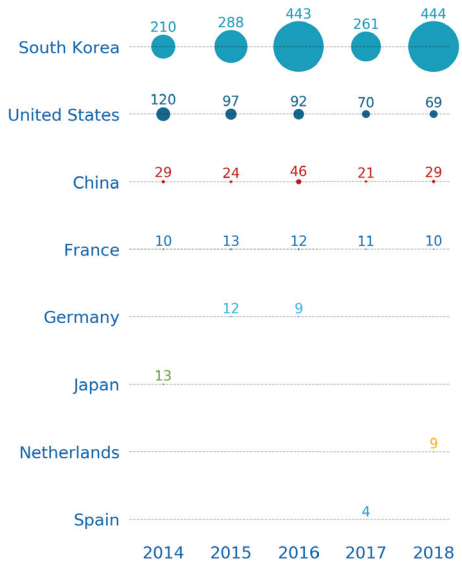
Organization	Country	Last Deal ($MM)	Deal Type
View	USA	$1,100	Series H
ofo	China	$866	Series F
Ramky Enviro Engineers	India	$600	PE
Hello TransTech	China	$582	Series G
Cambridge Mobile Telematics	USA	$500	VC

PE = Private Equity, VC = Venture Capital (Unspecified)

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$8.6 billion
IN VENTURE CAPITAL 2018

88%
COMPOUND ANNUAL GROWTH 2014-2018

CYBERSECURITY, PRIVACY, AND TRUST

2018 brought front-page stories about abuse of personal data by social media companies, ongoing cyberattacks compromising personal and financial information, and growing concerns about the rise of a global surveillance state. These are complex issues, and it is likely that new technologies will emerge that empower individuals and organizations to protect their data and identities from governments, corporate marketers, and malicious actors. Many of these technologies could find dual-use in the Army, especially in the special operations community. At the same time, technologies such as "adversarial objects" could defeat Army surveillance systems.

EMERGING CAPABILITIES

» Fooling Facial Identification

Researchers at Carnegie Mellon have demonstrated "adversarial glasses" capable of fooling state-of-the-art facial recognition algorithms. The glasses are inconspicuous to onlookers and enable the wearer to either impersonate other individuals or dodge recognition systems altogether.

» IoT Security

Intel predicts 200 billion internet-of-things (IoT) devices will be online by 2020 - approximately 26 devices per person. Most IoT devices and sensors lack any form of security, leaving both individuals and IoT-monitored infrastructure vulnerable to cyberattack.

» AI–Powered Facial Recognition

Chinese companies like SenseTime and Megvii are world leaders in AI-powered facial recognition. Megvii's open-source facial recognition platform, Face++, is used by over 300,000 developers worldwide. Chinese police in Zhengzhou are testing camera-equipped sunglasses powered by Face++ that can recognize suspected criminals.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Chinese Academy of Sciences	China	2,517
Beijing University of Posts and Telecommunications	China	1,221
Ministry of Education China	China	1,157
Xidian University	China	1,134
CNRS Centre National de la Recherche Scientifique	France	1,089

TOP PATENT HOLDERS, 2014-2018

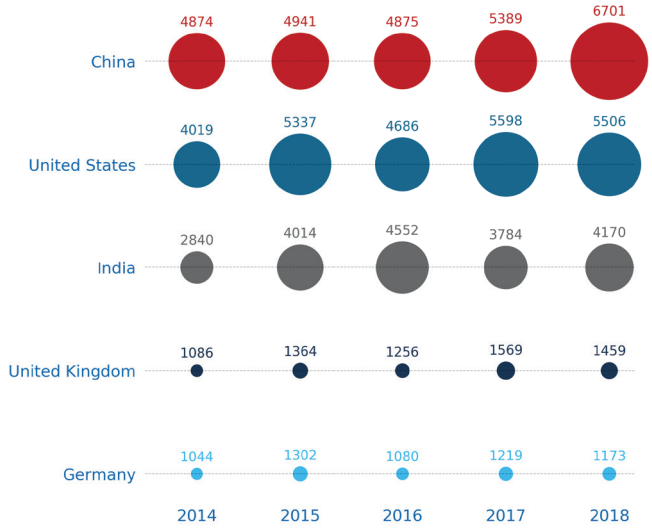
Institution	Country	# of Patents
Samsung Electronics Company	South Korea	2140
Ibm (International Business Machines Corporation)	USA	1658
Intel Corporation	USA	1389
Huawei Technologies Company	China	1289
Qualcomm	USA	1002

Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

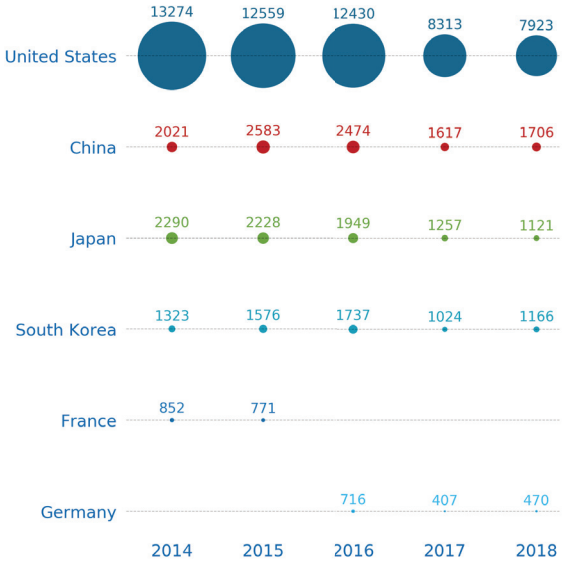
TOP VENTURE CAPITAL DEALS, 2018

Organization	Country	Last Deal ($MM)	Deal Type
SenseTime	China	$1,000	Series D
CrowdStrike	USA	$200	Series E
Netskope	USA	$169	Series F
CloudWalk Technology	China	$144	Series B
Cylance	USA	$120	Series E

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$8 billion
IN VENTURE CAPITAL 2018

62%
COMPOUND ANNUAL GROWTH 2014-2018

DIGITAL REALITY

Mixed reality blends virtual and augmented reality, creating environments in which physical and virtual objects co-exist. The technology has wide-ranging applications in immersive entertainment, training, medical care, design, and many other fields. In a related vein, digital mimicry technologies can create hyper-realistic computer-generated models of individuals. By 2048, it is likely that digital mimics will be indistinguishable from real people. While the technology has obvious applications in digital entertainment, malicious actors could create "deep fakes" of world leaders, military commanders, and other key figures, sowing disinformation and compromising chains of command.

EMERGING CAPABILITIES

» Generalized Adversarial Networks

Engineers at NVIDIA published research on a generalized adversarial network (GAN) that can produce synthetic images of people complete with high-resolution hair, facial expressions, freckles, and other fine details. In most cases, the images are indistinguishable as fakes.

» Practical Head-Mounted Displays

Chinese startup Nreal is releasing a pair of augmented reality glasses that weighs just under 3 ounces. Unlike other head-mounted displays, this product looks like normal sunglasses and delivers 1080p resolution at a field of view comparable to bulkier offerings by Microsoft and Magic Leap.

» Deep Video

A team of scientists from Germany, France, the UK, and the US published research in August 2018 on a technique for making photo-realistic fake videos of individuals from real video samples. The technique reproduces 3D head position and rotation, face expression, eye gaze, and blinking. People viewing videos of world leaders produced by the algorithm rated the synthetic videos as real nearly 50% of the time.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
CNRS Centre National de la Recherche Scientifique	France	503
Chinese Academy of Sciences	China	439
University of Tokyo	Japan	366
University of Southern California	USA	353
Technical University of Munich	Germany	348

TOP PATENT HOLDERS, 2014-2018

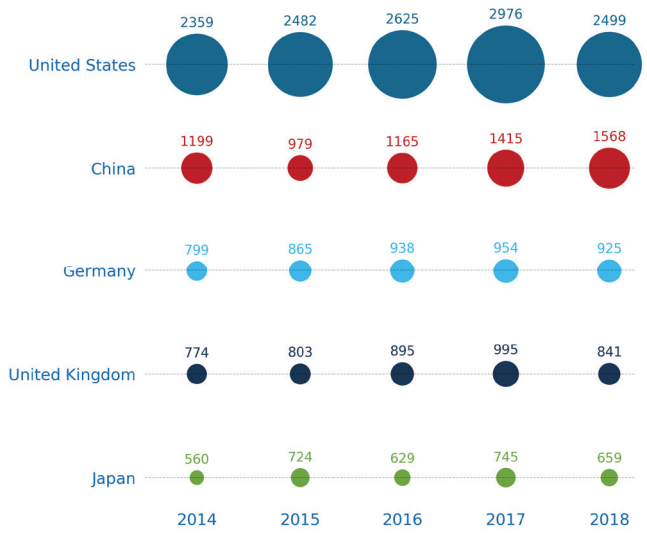
Institution	Country	# of Patents
Microsoft Technology Licensing	USA	416
Seiko Epson Corporation	Japan	414
Magic Leap	USA	377
Google	USA	325
Samsung Electronics Company	South Korea	244

Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

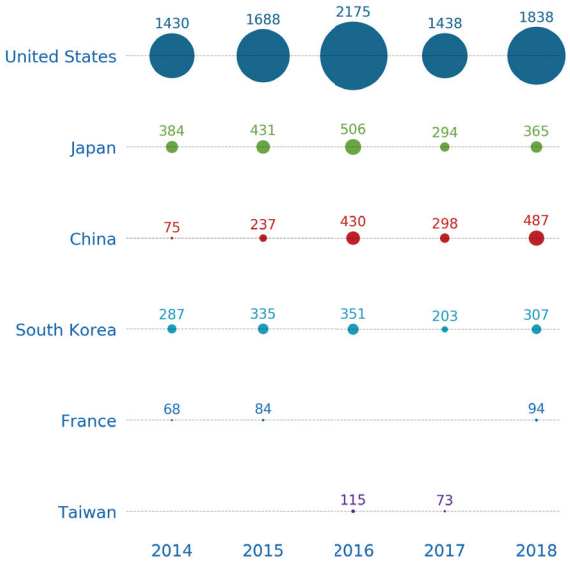
TOP VENTURE CAPITAL DEALS, 2018

Organization	Country	Last Deal ($MM)	Deal Type
Magic Leap	USA	$461	Series D
Niantic	USA	$191	Series C
Roblox	USA	$150	Series F
Zwift	USA	$120	Series B
Rokid	China	$100	Series B

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$5.6 billion
IN VENTURE CAPITAL 2018

82%
COMPOUND ANNUAL GROWTH 2014-2018

ENERGY

The U.S. Energy Information Administration projects a 28% increase in global energy use by 2040. Most estimates assume fossil fuels will remain key to meeting increased demands. However, renewable energy sources such as solar and wind are nearing broad-based cost-parity with fossil fuels. Iceland and Costa Rica already generate most of their power from renewable sources, and China is making massive investments in solar infrastructure and manufacturing. A shift to renewables could lead to new conflicts over reserves of materials needed for batteries, solar cells, and other key systems. Declining reliance on fossil fuels could also destabilize economies in nations dependent on oil and gas exports.

EMERGING CAPABILITIES

» Perovskite Solar Cells

Perovskite solar cells (PSCs) can convert over 20% of solar energy to electricity. PSC efficiency is limited by ion defects that drift through the cell over time. Researchers from the UK have developed a novel way to adjust the PSC layers such that reduces the impact of these defects, potentially boosting efficiency even further.

» Controlling Fusion Reactor Stability

Scientists at the U.S. Department of Energy have discovered a way to control dangerous plasma instabilities in fusion reactors. The process controls the size of magnetic islands, bubble-like structures that can halt fusion reactions and damage reactors.

» Fuel Cell Catalysts

A catalyst developed by researchers at UC, Berkeley, can generate hydrogen fuel from water as efficiently as costly platinum catalysts. The new catalyst is composed of nanometer-thin sheets of molybdenum, tungsten, or cobolt mixed with ordinary gelatin.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Chinese Academy of Sciences	China	14,747
Ministry of Education China	China	13,231
Tsinghua University	China	6,795
Xi'an Jiaotong University	China	4,799
University of Chinese Academy of Sciences	China	4,292

TOP PATENT HOLDERS, 2014-2018

Institution	Country	# of Patents
Toyota Motor Corporation	Japan	6,759
Lg Chem	South Korea	4,191
Samsung Sdi Company	South Korea	3,697
Toshiba Corporation	Japan	2,804
Panasonic Intellectual Property Management	Japan	2,548

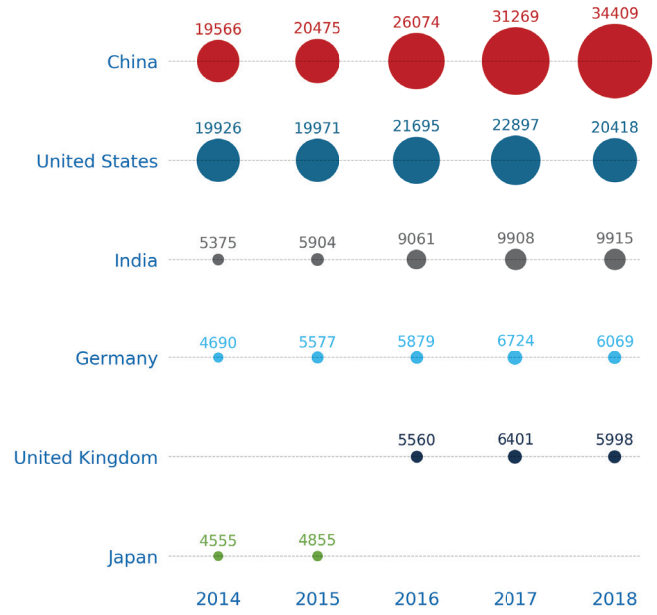
Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

TOP VENTURE CAPITAL DEALS, 2018

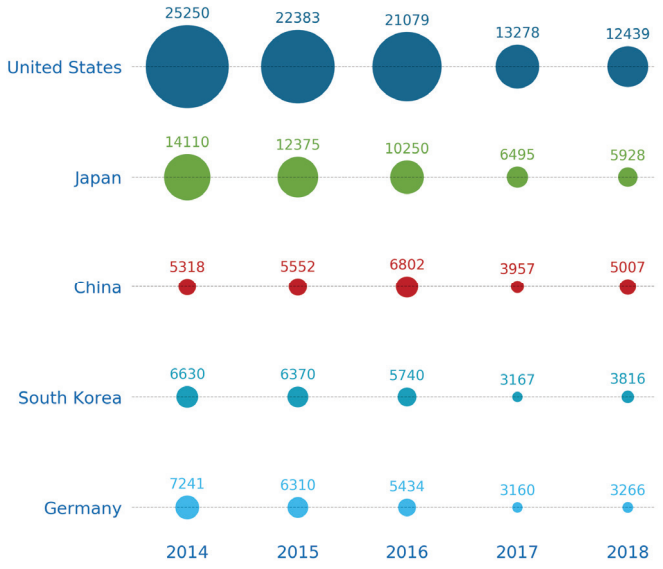
Organization	Country	Last Deal ($MM)	Deal Type
Farasis Energy	USA	$790	Series C
Artic Green Energy	Iceland	$150	VC
Quantumscape	USA	$100	CR
Kokam	South Korea	$88	CR
Etagen	USA	$83	Series C

CR = Corporate Round, VC = Venture Capital (Unspecified)

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$6.4 billion
IN VENTURE CAPITAL
2018

31%
COMPOUND ANNUAL GROWTH
2014-2018

QUANTUM COMPUTING

Long-hyped as an emerging revolution, quantum computing has been slow to show practical applications. That has begun changing rapidly, with companies in Canada, the US, Europe, and China demonstrating quantum computers that approach what IBM has referred to as "quantum dominance" - the point at which a quantum computer exceeds the performance of any classical computer. Quantum computers could transform drug discovery, enable simulations of novel materials for batteries, and lead to impervious encryption. On the other hand, the U.S. National Academy of Sciences estimates that traditional encryption schemes could be quickly cracked by a quantum computer.

EMERGING CAPABILITIES

» Quantum Key Distribution

Researchers in South Korea demonstrated the first quantum key distribution (QKD) in daylight. The system achieved a secure key transmission rate of 142.94 kbps with a quantum bit error rate of 4.26% in daylight over a distance of 275 meters.

» Quantum Metrology

China is opening a $10 billion National Laboratory for Quantum Information Science in 2020 that will focus on applied quantum computing and quantum metrology (using quantum effects to measure minute changes in gravity, mostly for position, navigation, and timing applications).

» Quantum Communications

In 2016, China launched the first satellite dedicated to testing quantum communication. In 2018, Chinese scientists used this satellite to distribute entangled photons to pairs of ground stations in China up to 1200 km apart. This represents a major breakthrough in secure quantum communications.

TOP INSTITUTIONS BY ACADEMIC PUBLICATIONS, 2014-2018

Institution	Country	# of Publications
Chinese Academy of Sciences	China	1,088
CNRS Centre National de la Recherche Scientifique	France	879
University of Science and Technology of China	China	796
National University of Singapore	Singapore	556
University of Waterloo	Canada	543

TOP PATENT HOLDERS, 2014-2018

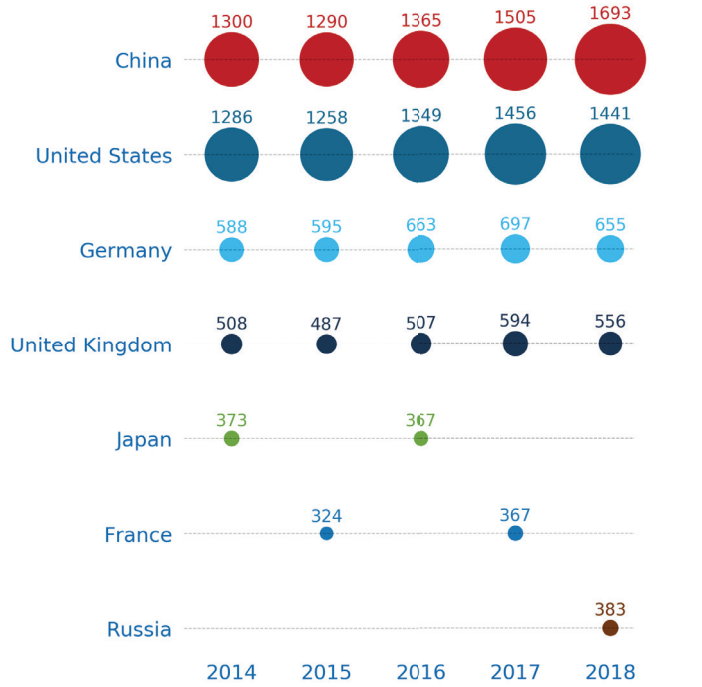
Institution	Country	# of Patents
Intel Corporation	USA	88
D-Wave Systems	Canada	82
Toshiba Corporation	Japan	76
Shenzhen China Star Optoelectronics Technology Company	China	69
IBM	USA	59

Based on priority applications and grants filed with the USPTO, EPO, JPO, or WIPO.

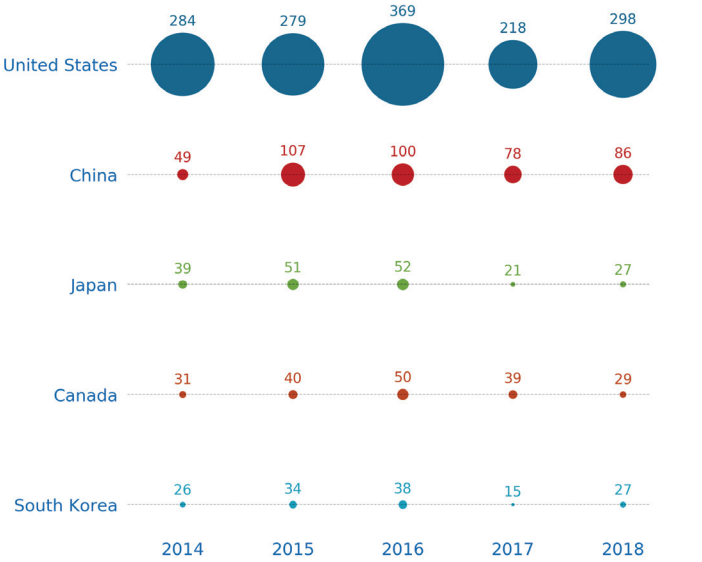
TOP VENTURE CAPITAL DEALS, 2018

Organization	Country	Last Deal ($MM)	Deal Type
D-Wave Systems	Canada	$10	Grant
ISARA Corporation	Canada	$10	Series A
Xanadu	Canada	$6.9	Seed
ColdQuanta	USA	$6.8	Seed
QC Ware	USA	$6.5	Series A

TOP COUNTRIES BY ACADEMIC PUBLICATIONS, 2014-2018



TOP COUNTRIES BY PATENTS GRANTED, 2014-2018



$2.8 billion
IN VENTURE CAPITAL 2018

13%
COMPOUND ANNUAL GROWTH 2014-2018

DISCLAIMER

This report was prepared for the Deputy Assistant Secretary of the Army (Research & Technology) by FutureScout, LLC, a strategy and analytics firm specializing in helping organizations understand emerging trends and how to prepare strategically to thrive in the face of an uncertain future. Questions regarding the preparation of this report may be directed to:

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