Policy Challenges of Accelerating Technological Change: Security Policy and Strategy Implications of Parallel Scientific Revolutions

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Executive Summary

This paper examines policy, legal, ethical, and strategy implications for national security of the accelerating science, technology, and engineering (ST&E) revolutions underway in five broad areas: biology, robotics, information, nanotechnology, and energy (BRINE), with a particular emphasis on how they are interacting. The paper considers the timeframe between now and 2030 but emphasizes policy and related choices that need to be made *in the next few years* to shape the future competitive space favorably, and focuses on those decisions that are within U.S. Department of Defense's (DoD) purview. The pace and complexity of technological change mean that linear predictions of current trends *cannot* be the basis for effective guidance or management for the future. These are issues for policymakers and commanders, not just technical specialists. The summaries below highlight a few of the developments and implications in each area. The body of the paper includes significantly more detail.

Transformational advances in **biology, biotechnology, and medicine** include personalized and regenerative medicine, neuroscience, brain mapping, biomanufacturing, and synthetic biology.

Progress in **robotics, artificial intelligence, and human augmentation** is enabling advanced unmanned and autonomous vehicles for battlefield and hazardous operations, low-cost autonomous manufacturing, and automated systems for health and logistics.

Advances in **information and communications technologies (ICT) and cognitive science** are being driven by trends such as speed, mobility, commoditization/open source, big data, the cloud, and the Internet of (Every)Thing. They are complemented by advanced decision-support tools and exotic computing architectures such as quantum computers.

Advances in **nanotechnology and advanced materials** include high-performance materials, multi-functional smart materials, highly energetic explosives, and nanomaterials as components of advanced electronics, and in medicine and biotechnology.

Energy initiatives need to begin with demand reduction, whether through policy, process, or design. Other new technologies include improved renewable generation, exotic storage technologies, smart power grid management, and better power sources for directed-energy weapons (DEW). Accessible partner nation biofuel initiatives could enhance operational flexibility.

Many of these areas, and especially their convergence, will result in **disruptive new capabilities** for DoD which can improve warfighter performance, reduce health-care and readiness costs, increase efficiency, enhance decisionmaking, reduce human risk, improve biochemical defense, enable pervasive sensing and distributed command and control, and support expeditionary energy and base resilience. However, U.S. planning must expect that many of these also will be available to adversaries who may use them under very different ethical and legal constraints than we would.[1]

[1] The need to consider advanced capabilities in adversary hands is stressed in: Robert O. Work and Shawn Brimley, *20YY: Preparing for War in the Robotic Age*, Center for New American Studies, 2014, http://www.cnas.org/sites/default/files/publications-pdf/CNAS_20YY_WorkBrimley.pdf

This study focuses on a few broad policy, strategy, legal, ethical, organizational, and related areas that can help shape the national security consequences of these technological changes and their interactions. Recommendations include the following:

Foresight: Expand and institutionalize DoD capabilities for strategic foresight, adaptive management, and technological intelligence. [2] These capabilities can enhance DoD's global awareness, improve strategic decisionmaking, and facilitate better investment decisions.

International Governance: Examine ways that DoD can help shape the long-term security consequences of trends in international technology governance and standards bodies (e.g., the International Telecommunications Union and the International Organization for Standardization).

Public-Private Cooperation: Recognizing that private sector innovation and investment is increasingly important for national security, develop a policy, legal, contractual and values framework to let DoD leverage private sector resources better, both domestically and overseas.

Future Workforce Development: Examine the impacts of accelerating technology, generational change, and cultural evolution on the future DoD workforce, including jobs displaced by automation. Leverage innovative learning and private sector concepts to build new models for the workplace.

This summary highlights only a few of the important policy issues that are addressed more fully in the body of the paper, such as (1) recognizing science, technology and engineering (ST&E) capacity and its geographic distribution as a strategic variable (i.e., *GeoInnovation*), (2) establishing proactive DoD positions on expanding privacy issues, (3) protecting and enabling the future defense technology and industrial base, (4) facilitating DoD's energy-related initiatives, and (5) addressing critical issues of ICT and cyberspace. In addition, the paper addresses policy, legal, and ethical issues related to unmanned and autonomous systems, DEW, and biotechnology.

Maintaining DoD's present technological preeminence will be a difficult challenge. Many dedicated people are addressing the technology issues, but policy actions also will be crucial to adapt to—and shape—the technology component of the international security environment. Addressing these issues in the near term will help to mitigate risks and improve outcomes.

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[2] Forecasting typically extrapolates predictions based on already identified trends, whereas foresight tries to anticipate the broad range of possibilities that could emerge from developing strategic conditions, ideally incorporating a wide range of synthetic, holistic or creative perspectives. These can help assess impacts and facilitate planning to improve outcomes.

1. Overview

New technological developments are increasingly affecting every aspect of global society, and the pace of technological innovation is accelerating. The development and production of new technologies is also becoming increasingly globalized, with many nations now investing significant resources in scientific and commercialization infrastructure. A number of prestigious studies have raised serious concerns that this increasing competition will result in a loss of technological preeminence by the United States.[3] These trends are particularly worrisome for future U.S. military capabilities, which have been based on technological dominance for decades.

Technological development today involves a highly complex interplay between elements such as research, finance, infrastructure, education, economics, and government policy, often referred to as an *innovation ecology*. Similarly, the adoption and use of technologies to create *capabilities* also involves interactions among people, processes, organizations, policies, and governance, as well as technology. It is within these areas that DoD is finding itself increasingly challenged as it tries to adapt to and exploit rapid technological change. Failure to overcome these hurdles will result in increasing technological obsolescence, and, eventually, diminished national power.

Within this context, this paper examines policy, legal, ethical, and strategy implications for DoD from the impact of the accelerating ST&E revolutions that are underway in five broad areas: (1) biology, biotechnology and medicine; (2) robotics, artificial intelligence, and human augmentation; (3) ICT and cognitive science; (4) nanotechnology and advanced materials; and (5) energy technology (collectively, BRINE).[4] Although the principal focus is on the changes in technology between now and 2030, this study emphasizes policy and related choices that need to be made *in the next few years* to help shape the future competitive space to maintain DoD technological dominance as far as possible. As such, the study emphasizes the impacts of nonlinear change, cross-cutting synergies among technologies, and rapidly evolving socio-economic, geopolitical, and resource trends more than the technologies themselves. It makes several recommendations focused on building capacity and resilience despite disruptive change over the coming decades, exploiting new capabilities, and mitigating potential risks—even in a time of sustained budget austerity and evolving global competition.

1.1 Policy Context

DoD thinking about emerging technologies has evolved in recent years. In January 2012, U.S. Defense Secretary Leon Panetta issued a new strategic guidance document[5] for the Department, followed in February by the document, *Strategic Direction to the Joint Force*, by General Martin Dempsey, Chairman of the Joint Chiefs of Staff. Both documents focused on 2020, describing

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[3] For example, *Rising Above the Gathering Storm, Revisited*, National Academies Press, 2010, http://www.nap.edu/catalog.php?record_id=12999

[4] We are indebted to Mr. Frank Hoffman for the BRINE formulation. Other groupings are possible. Some studies group AI with ICT. Some technologies, such as Directed-Energy Weapons (DEW) are addressed as the convergence of new power supplies, beam forming and pointing/tracking. Others, such as space technologies are only addressed peripherally since most don't involve new core science. Others, such as fundamental breakthroughs in physics (dark matter, dark energy, etc.) are not included because they are not likely to demand key DoD policy decisions within the next few years.

[5] For an analysis of these documents, see: *Strategic Shift: Appraising Recent Changes in U.S. Defense Plans and Priorities*, by Richard Kugler and Linton Wells, CTNSP, National Defense University, 2013. An online update is available to include the 2014 QDR and the FY15 Budget Request.

the changing geopolitical security environment, the primary missions of our armed forces, and principles to shape the development of future defense programs. There was not much in the Defense Strategic Guidance (DSG) document about technology, prompting an op-ed piece[6] by one of this paper's authors. Later, however, the Capstone Concept for Joint Operations (CCJO) added a considerable emphasis on technology; for example: "The diffusion of technology that is transforming warfare is also reshaping global politics." The 2014 Quadrennial Defense Review[7] also states "The United States will remain a global leader in the creative development and use of technology." Finally, a more general framework for DoD guidance is provided by the 2010 U.S. National Security Strategy, which addresses broader technology issues beyond DoD. For example, it highlights the need for the United States to emphasize education and energy, promote private-sector innovation, and stay "on the cutting edge of science and innovation that supports our prosperity, defense and international technological leadership."

Respected organizations such as the National Intelligence Council, the Defense Science Board, and several think tanks are looking at technology trends in detail. Appendix A lists some of the important trends and emerging technologies identified in several recent studies. This paper also considers technology trends out to 2030 but, in contrast, focuses on "nonmaterial" issues within DoD's analytical structure of doctrine, organization, training, material, leadership, personnel, facilities and policy (DOTMLPF-P).

The increasingly rapid pace of technological change is affecting not only threats or specific mission areas but also fundamental features of the global security environment. Ongoing developments are nonlinear, often unexpected, and sometimes disruptive. Increasingly they affect all aspects of global society. Linear projections based on current trends *cannot* provide an effective basis for future planning. This study therefore aims to flag for DoD leadership some key policy issues raised by these accelerating technological trends, especially those that need to be addressed in the near term (i.e., the next 2 to 3 years).

1.2 Accelerating Technological Change and the Globalization of ST&E

To illustrate the potential for technological change in the 16 years until 2030, it is instructive to consider the evolution of the science, technology & engineering (ST&E) landscape over the last 16 years. In 1998, the human genome had yet to be sequenced; today, personal genome sequencing products are entering the commercial market. Twitter and Facebook did not exist, and Google had just been founded; today, social media is an integral part of the public's daily experience and is becoming mainstream, while the collection, analysis, and display of huge amounts of information underpins much of today's economy and governance. In robotics, few unmanned vehicles were fielded by the U.S. military; today, thousands of unmanned aerial vehicles are routinely employed on complex public and private missions, and unmanned ground and sea vehicles are becoming common. The field of nanotechnology was still a relatively obscure science; today, more than 1,000 commercial products contain nanotechnology components, with a potential global market of $3 trillion by 2020. Also, in 1998 the prospects for U.S. energy independence were not encouraging; today, hydraulic fracking technology has created a boom in U.S. oil and gas production that may allow us to achieve that goal of energy independence by 2020. Beyond these examples, it is important to understand that because of the

[6] Linton Wells II, "Tech Changes Affect U.S. Security," *Defense News*, January 22, 2012 http://www.defensenews.com/article/20120122/DEFFEAT05/301220002/Tech-Changes-Affect-U-S-Security

[7] See http://www.defense.gov/pubs/2014_Quadrennial_Defense_Review.pdf, page 9.

accelerating rate of technological change today, the amount of change we can expect by 2030 is likely to be much greater than we have experienced since 1998, and it will be qualitatively different as technology areas become more highly integrated and interactive.

In another well-known example, "Moore's Law[8]" states that the number of transistors on a computer chip is doubling about every 2 years, a rate which has held true since the 1960s. If the trend holds, computing power per unit cost (a more general formulation) will increase by about 500% by 2020 and more than 12,800% by 2030.[9] More importantly, a recent analytic study[10] has found that a broader postulate, called Wright's Law, generically predicts similar exponential behavior for 62 technologies over several decades. Such rapid advances across a breadth of technology areas mean that it will become harder to predict the large-scale consequences of such technological change even in the relatively near future. In any case, linear projections of current trends simply **cannot** work in this environment.

Although attempts to forecast technological developments are not new, their methodologies and effectiveness are often debated.[11] As an example, in 2010 a study was done of the performance of an earlier long-term technology forecasting effort on behalf of Army S&T.[12] One of the things it found was that the impacts of several key advances were missed that related to the explosion of the Internet, IT and wireless applications, and social media. A follow-on analysis[13] noted, "…the missed areas were all stimulated by developments *outside* DoD and were more in the nature of very rapid technology exploitation in the marketplace, with unintended consequences for national security. As DoD becomes a smaller player in the global S&T enterprise, such missed forecasts are increasingly likely unless more robust [technology forecasting] methods are employed that involve broad-based participation of subject matter experts beyond DoD and the United States…"

In spite of these formidable challenges, a number of countries and organizations have developed successful foresight capabilities that have allowed them to anticipate elements of change, including technological change, build the capacity to mitigate its risks, and effectively exploit its development. [14] Doing so requires persistent, pervasive, and rigorous efforts to collect information, analyze and synthesize it, and, most importantly, integrate the resulting insights effectively into decisionmaking and planning. DoD will need to develop these capabilities in better ways to navigate a complex and uncertain future.

[8] It is recognized that "Moore's Law" is not a law, per se, but an observation that has proved useful over time.

[9] This projects 2 year doubling periods beginning in June 2014. Some suggest the doubling period is 18 months, in which case the increase in five years would be over 900%, in ten years over 10,000% and by 15 years over 100,000 percent (!). Others say the rate ultimately will slow. In any case, linear projections can't work.

[10] See *Statistical Basis for Predicting Technological Progress*, Santa Fe Institute, July 2012; see http://arxiv.org/pdf/1207.1463.pdf

[11] For example, see this DoD ATL report comparing performance of different methods of technology forecasting: www.dtic.mil/get-tr-doc/pdf?AD=ADA568107

[12] *Improving the Army's Next Effort in Technology Forecasting*, J.W. Lyons, R. Chait, and S. Erchov (ed), NDU Defense & Technology Paper Number 73 (2010). http://ctnsp.dodlive.mil/files/2013/07/DTP-073.pdf

[13] *Globalization of S&T: Key Challenges Facing DOD*, Timothy Coffey and Steven Ramberg, NDU Defense & Technology Paper Number 91 (2012), p. 33. http://ctnsp.dodlive.mil/files/2013/08/DTP-091.pdf

[14] For example, foresight methods for government policy are used increasingly in the EU and Singapore; see http://www.iss.europa.eu/fileadmin/euiss/documents/Books/Yearbook/2.1_Foresight_in_governments.pdf, and www.**rahs**.org.sg/ and http://www.csf.sg/

1.3 GeoInnovation

A fundamental, if disquieting, reality is that the concepts, outputs, and interactions of the BRINE technologies will profoundly affect the future international security environment in ways that cannot be controlled by the United States, much less the U.S. military. This reality will be exacerbated by the fact that America's share of global research is steadily declining. One estimate is that America's fraction of the global S&T enterprise will shrink from 26% today to about 18% by 2050. [15] Even more problematic is that U.S. defense research represents a diminishing percentage of U.S. research output, and future budgetary challenges may accelerate this trend. For example, in the 1970s, DoD S&T personnel represented about 1/20th of the total researchers in the world, whereas today they represent about 1/800th of the world's total.[16] If these trends continue, the U.S. military faces the very real prospect of losing its technological preeminence in important areas.

While these trends should be a source of concern by themselves, perhaps more important is the way current ST&E capacities are distributed globally. Many other countries have now embraced ST&E as a key enabler of economic growth, social change, diplomacy, and military capabilities. ST&E innovations increasingly come from a distributed geographic landscape of national and private sector entities, many of which view themselves as direct competitors to U.S. interests. This trend will only intensify, and the opportunities and risks it provides need to be addressed as strategic issues. Section 2.1.2 therefore proposes the development of *GeoInnovation* as a new strategic variable to monitor these trends and analyze their future impacts.

A 2010 workshop by the Asia-Pacific Center for Security Studies investigated the potential influence of emerging technologies on future international security and reached several important conclusions.[17] For example, "There is a direct correlation between a country's place in the global hierarchy and S&T capabilities. Modern technology is central to the pursuit of national goals for all nations - big or small. However, the pace of technological change across continents and countries is never uniform…. In a globalized world, technology access and technology denial play key roles in determining the fate of nations." And, "In short, the technologies of the future will once again determine the fate of nations."

Yet, in spite of this increasing importance of the globalization of science, technology, and commercialization resources, DoD and the United States in general pay relatively little attention to building the capabilities necessary to track these changes, leverage these resources, and account for their potential effects in national policy, strategic planning, and budgeting processes. These facts, however, have not been lost on other countries, many of which are becoming increasingly more organized and effective at harvesting resources, talent, and intellectual property from the global ST&E enterprise.[18]

For DoD to remain a technological leader in the coming decades, it must start *today* to build the capabilities to understand and harvest benefits of the complex global ST&E environment, as well as prepare for its potential effects on our future national security. A recent report by the Center

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[15] Coffey and Ramberg, DTP 91, *op.cit.*, p.1

[16] *Ibid*, p. 17

[17] The *Interface of Science, Technology, and Security*, APCSS Workshop proceedings; see http://www.apcss.org/college/publications/the-interface-of-science-technology-security/

[18] Aside from well known efforts by major powers such as China and Russia, other countries rapidly building their S&T capacity include Iran, Vietnam, and India.

for a New American Security observed that “retaining technological dominance is a strategic choice… the nation must actively break down the bureaucratic antibodies that resist investment in innovation and redouble its focus on sustaining technological dominance.”[19] Secretary Hagel also recently stated, “We must maintain our technological edge over potential adversaries,” adding that, “the military must be ready and capable to respond quickly to all contingencies and decisively defeat any opponent should deterrence fail.”[20] And for the U.S. armed forces to remain, as Secretary Panetta termed it, “the world’s finest military,” our investment in and understanding of key technological opportunities and risks should be as much a part of global strategy debates as geopolitics, demographics, economics, and the nature of conflict.

1.4 Synergistic Technology Revolutions

By any historical measure, the pace of innovation in ST&E today is very fast, and it continues to accelerate. Diverse factors underlie this behavior. In the basic sciences, the information revolution has made widely available new concepts, vast online databases, powerful modeling and analysis methods, and collaborative tools that greatly enhance the speed of new discovery. The development of new technologies benefits from these same factors but also includes economic factors related to commercialization and deployment and is increasingly driven by tools for e-commerce, e-marketing, crowdsourcing, and crowdfunding. Another factor driving this rapid innovation is the globalization of ST&E, as even developing nations are now funding and developing advanced ST&E capabilities in hopes of generating high-value economic growth. International organizations such as the Organization for Economic Cooperation and Development (OECD),[21] as well as the U.S. Department of State and the U.S. Agency for International Development (USAID),[22] increasingly view ST&E as a tool of diplomacy, cooperation, and mutual economic development. Finally, an increasingly important factor is the cross-fertilization of concepts, tools, and methods in research and engineering disciplines, particularly in the rapidly evolving areas of BRINE.[23] Each of these technological areas benefits from new innovations and tools developing in the other areas, and it is at the intersection of these disciplines that some of the most rapid and unexpected technological innovation is occurring, with the greatest national security implications.

To support the policy focus of this paper, a study was conducted of the current landscape and future trends of the five elements of the BRINE technologies. Detailed descriptions of the results are contained in Appendices B–F. This section contains a brief summary of the appendices to provide a context for the policy, legal, ethical and other recommendations.

Biology, Biotechnology, Medicine: The biological sciences today are experiencing the kind of profound transformation that the field of physics did over a century ago. Principal drivers of this revolution include genomics and gene-mapping technologies; mathematical modeling and bioinformatics; advanced materials for sensors, characterization, and medical devices; and increasingly integrated microelectronics and nanotechnologies. These advances are already

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[19] *Game Changers: Disruptive Technology and U.S. Defense Strategy*, Center for a New American Security, 2013; available at: http://www.cnas.org/files/documents/publications/CNAS_Gamechangers_BrimleyFitzGeraldSayler.pdf
[20] See http://whnt.com/2014/02/24/defense-secretary-chuck-hagel-to-recommend-deep-budget-cuts-targeting-pay-benefits/
[21] See http://www.oecd.org/
[22] See http://www.usaid.gov/
[23] See “U.S. seen as weak on global research collaboration, ”*International New York Times,”* July 21, 2014, p. 7

resulting in the development of numerous transformational technologies and applications, such as rapid biochemical detection and characterization, genetic modification of organisms, personalized medicine, stem cells and regenerative medicine, neuroscience and brain mapping, and synthetic biology. These developments will have major ramifications for DoD with respect to improving warfighter performance, lowering health-care costs, ensuring biochemical defense, promoting counterterrorism, and augmenting human cognition. However, there are important legal, policy, and ethics issues related to these emerging technologies, including asymmetries in cultural norms and political perceptions potential opponents have about their use.

Robotics, Artificial Intelligence, and Human Augmentation: After decades of research and development, a wide range of technologies is now being commercialized that can augment or replace human physical and intellectual capabilities. Advances in sensors, materials, electronics, human interfaces, control algorithms, and power sources are making robots commercially viable—from personal devices to industrial-scale facilities. Several countries, including the United States, now have large-scale national initiatives aimed at capturing this burgeoning economic sector. Artificial intelligence has also made major advances in recent years, and although still limited to "weak" artificial intelligence, or AI, general-purpose artificial intelligence may be available within a decade. Transformational applications include low-cost autonomous manufacturing, health and medicine, advanced autonomous vehicles for battlefield and hazardous operations, smart logistics, and, increasingly, embedded systems and the Internet of Things (IoT). The IoT, which increasingly is being referred to as the "Web of Everything," also links closely with developments in ICT.[24] Developments like exoskeletons and direct brain-machine interfaces can combine with contributions from bioscience and cognitive science to augment human performance significantly. These technologies have great promise for DoD in reducing manpower requirements, improving health care and lowering costs, increasing efficiency, enhancing decisionmaking, and reducing risks to humans. However, important policy, legal, and ethical considerations now are surfacing in this area, such as the use of drones in U.S. airspace or how to control autonomous weapons systems lacking human supervision (i.e., "Kill Bots"). As an important study points out, other countries and the private sector are taking the lead in these areas, and the United States must begin to prepare for warfare in the robotic age.[25]

Information and Communication Technologies and Cognitive Science: The development and deployment of new ICT continues to underpin some of the greatest changes in human history. Advances are being driven by widespread interest in speed, mobility, commoditization/open source development, big data, the cloud, and the IoT (Web of Everything). As the digital networking of people and devices continues to accelerate, from micro-sensors to global networks, the volume of information online is increasing at an exponential rate. ICT are also greatly facilitating research and development in ST&E areas across the BRINE framework. Emerging technologies and capabilities include ubiquitous sensing, ubiquitous network access, big data, increasingly sophisticated social media, virtual reality and telepresence, advanced decision-support tools, and exotic computing architectures, such as quantum computers. As humans struggle to comprehend this sea of information, cognitive science is becoming more important,

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[24] Since early 2014, commentators have been extending references about the "Internet of Things" to the "Internet of Everything" as, for example, the human body increasingly becomes a platform for wearable and embedded devices; See for example: http://internetofeverything.cisco.com/ The "Web of Everything" suggests that devices and services can interact directly with less dependence on the underlying infrastructure.

[25] Robert O. Work and Shawn Brimley, *20YY: Preparing for War in the Robotic Age*, Center for New American Studies, 2014, http://www.cnas.org/sites/default/files/publications-pdf/CNAS_20YY_WorkBrimley.pdf

and rapid advances are being made in understanding and augmenting human cognition. These can contribute to advanced capabilities for pervasive environmental sensing and situational awareness, open source Intelligence, Surveillance, and Reconnaissance (ISR), smart logistics, distributed Command-Control-Communications-Computers (C4), education and training, improved human creativity, and even strategic communications and humanitarian support. However, DoD has also found itself increasingly challenged with being able to acquire and exploit cutting-edge ICT on competitive timelines and defend against a wide range of new threats and malicious actors.

Nanotechnology and Advanced Materials: Advances in materials have been central to human progress for millennia. Today, the revolutions in new materials and nanotechnology are becoming comparable to the revolutions in biology and ICT. Advanced materials, such as hybrid composites and multi-functional materials, are already providing significantly improved performance and lowered weight and cost to a wide range of products. Nanotechnology, a collection of tools and methods to manipulate matter at the atomic scale, now spans nearly all research and engineering disciplines, and product development is increasing in every business sector. Potentially transformational technologies and capabilities include multi-functional materials (e.g., combined physical, electrical, and optical properties), micro- and meta-materials, smart materials, nanomaterials, nanoelectronics, nanomedicine and pharmaceuticals, and highly functionalized nanodevices, such as nanosensors and nanomachines. Advanced materials have the potential to revolutionize almost every technology and industrial sector and could also apply, for example, to conformal antennas and power supplies for DEW. Related methods for advanced manufacturing also are important, and global competition is now fierce to develop and commercialize them. DoD could benefit from them across a wide range of application areas; however, it will be a significant challenge for DoD and the United States in general to maintain technological and commercial leadership in the face of increasing globalization.

Energy: After decades of research, many new energy technologies are now being commercialized, facilitated by advances in other areas of BRINE. Particular focus areas in the United States have been on alternate energy sources, new storage methods, increased efficiency, and smart energy management. The last two areas are exceptionally important, along with effective design, since demand reduction is the first step in efficient energy use.[26] Areas that are now maturing and are potentially transformational include advanced solar cells, biofuels, exotic batteries, next-generation fuel cells, ultracapacitors, energy harvesting, and smart power grid systems. These capabilities have many DoD applications, for example, for expeditionary energy for ourselves and our partners. However, in just the last few years, the global landscape of energy production has seen a seismic shift, as vast North American reserves of oil and gas have been unlocked by hydraulic fracking and horizontal drilling. This will have not only profound consequences for U.S. energy security and economic growth but also almost certainly a significant impact on geopolitics, as influence shifts among major producers. As the largest operator of facilities and vehicles in the world, DoD has pursued and should continue to pursue alternate energy sources and increased efficiencies; however, the commercial viability of non-fossil energy sources may once again come into question as oil and natural gas prices drop. A number of important policy choices are now presenting themselves; for example: What policy and operational guidance could significantly reduce DoD demand for energy across multiple

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[26] Amory B. Lovins and Rocky Mountain Institute, *Reinventing Fire*, White River Junction, Vermont, Chelsea Green Publishing, 2011, p. xiii. Summary at: http://www.rmi.org/reinventingfire

technologies? Could DoD significantly enhance its operational flexibility if it could negotiate agreements with allies and key coalition partners to make their biofuels usable in U.S. systems?

1.5 Disruptive Convergent Technologies

Convergent technologies are hybrid systems that incorporate novel or cutting-edge capabilities from two or more scientific or engineering disciplines. They often result in capabilities that are major leaps of innovation, sometimes with rapid and unexpected repercussions. The cell phone is such an example, as it largely reflected the engineering-level integration of several existing technologies rather than fundamentally new ones, but the combination provided radically new capabilities that have had profound global impacts.

As ST&E disciplines increasingly overlap, the cross-fertilization of concepts and tools across the BRINE areas is resulting in a number of rapidly developing ST&E areas that are truly new and potentially disruptive. Advances such as synthetic biology and 3D printing, particularly in Do-It-Yourself (DIY) communities, are potentially transformational, but also fraught with new risks. In biology, developments in human behavioral modeling, neuro-economics, and brain mapping are creating powerful new tools for understanding ourselves and society, all of which are affected by developments in informatics. In robotics and artificial intelligence, human augmentation and direct brain interfaces could stretch the boundaries of what it means to be human, and the potential threats and vulnerabilities are still unknown.[27] Cyberspace continues to expand and evolve at an unparalleled rate, and as it increasingly becomes a Web of Everything, many socio-political issues in the legal, ethical, security, and regulatory realms are surfacing. Tactically useful DEW are emerging from developments in power supplies, pointing and tracking, and advanced beam forming, including tools like meta-materials. They may change the face of modern warfare. The convergence of energy and new materials, plus ICT in advanced design and manufacturing, can contribute to hypersonics, which the Air Force considers transformational.[28] As autonomous systems such as commercial micro-UAVs and self-driving cars begin to interface with humans in intimate ways, thus changing the patterns of society, a host of new, poorly understood vulnerabilities will accompany the new functionalities. These technologies, by themselves, will certainly have national security opportunities and risks associated with them. However, since they are mostly developing in the private sector, and spreading rapidly through it, their economic, social, and political effects are felt globally. Since DoD exists within the larger framework of global society, it will be vulnerable to these larger changes and disruptions and will need to understand, anticipate, and adapt to them.

[27] In April 2014 one of the authors had a valuable conversation with some Naval Academy midshipmen and asked them what technologies they thought their children would use to befuddle them to the same degree they befuddle their parents now. Several answered that they thought it would be the convergence between info, bio, and robotics – "cyborgization," if you will. Instead of "Hey, mom and dad, I got a tattoo!" it could be, "Hey, mom and dad, I got an implant!" or "Suzie and I plan to hang out tonight and meld our brain waves." Or whatever….

[28] USAF's Hypersonics Road Map Sets a Long-Term View, http://aviationweek.com/awin/usaf-s-hypersonics-road-map-sets-long-term-view

2. Policy, Legal, Ethical, and Other National Security-Related Recommendations

By 2030, advanced technologies are likely to have moved beyond being the important enablers of economies, armed forces, and socio-political movements that they are today to becoming key components of the national security environment itself. During this period, however, the United States will find itself a steadily less dominant player in the global ST&E enterprise, and it will need to manage and exploit its ST&E resources more efficiently and effectively to remain at the cutting edge. This potential loss of technological leadership will occur even more rapidly for DoD, as many cutting-edge technologies increasingly will be developed in the private sector and by other nations. The 2014 Quadrennial Defense Review (QDR) states, "While the global technology landscape indicates that the United States should not plan to rely on unquestioned technical leadership in all fields, the Department must ensure that technological superiority is maintained in areas most critical to meeting current and future military challenges."[29] Several recent national security studies have recommended specific emerging technology areas and organizational changes on which DoD should focus to mitigate these trends. Seven of these studies are summarized in Appendix A. This section provides a set of broader recommendations that go beyond the technologies themselves and address the longer term issues of cultural change, management, and planning.

DoD and other national security agencies face significant challenges in identifying, procuring, and exploiting the most cutting-edge technologies and capabilities, and they will need to change their organizations and cultures to adapt to accelerating, interactive technological change. Most technologies are, by themselves, merely tools, but these tools are turned into *capabilities* when adopted and used by people, organizations, societies, and governments. They become effective when they are integrated into socio-technical systems, which involve learning, training, process development, strategy, and organizational and cultural adaptation. In DoD, these elements are captured within the DOTMLPF-P analytical structure described earlier. Some of the greatest hurdles that DoD faces in responding to accelerating technological change involve nonmaterial elements ("DOTmLPF-P"). Additionally, one of the greatest impediments to DoD innovation lies in its acquisition system; however, this is a challenge that has been debated for decades, and indeed there is another significant effort currently underway to reform the acquisition regulations, so we will not discuss it here.

Below are 12 sections offering cross-cutting recommendations that address these broader policy, legal, ethical, and organizational issues. They focus on areas that could have significant long-term impacts, but where there will be opportunities for shaping actions and capacity building within the next 2–3 years. These areas are as follows:

Cross-Cutting Areas

1. Foresight as an Integral Component of DoD Planning Processes
2. ST&E Capacity as a Strategic Variable (GeoInnovation**)**
3. International Technology Governance and Standards Bodies
4. Framework for Enhanced Collaboration With the Private Sector

[29] See page 25, http://www.defense.gov/pubs/2014_Quadrennial_Defense_Review.pdf

5. Expanding Privacy Issues
6. Impacts of Emerging Technologies on the Present and Future DoD Workforce
7. Future Defense Industrial and Technology Base

Technology-Specific Areas

1. ICT and Cyberspace
2. Energy
3. Unmanned and Autonomous Military Systems
4. Directed-Energy Weapons
5. Biotechnology

While these recommendations are focused on DoD leadership strategies, many of them will be most effective if coordinated with the leadership of other Federal agencies, the states, the private sector, academia, and other countries and international organizations. This may seem a daunting challenge; however, models exist outside the United States, where other countries are effectively using foresight, strategic planning, and international engagement to enhance their ST&E enterprises and become technological and economic leaders. The United States can and must address these choices.

The remainder of this section covers these recommendations in detail. Sections 3.1.1 to3.1.7 deal with cross-cutting topics across several of the ST&E revolutions areas; Sections 3.2.1 to 3.2.5 are more focused on specific technologies.

2.1 Cross-Cutting Areas

2.1.1 Foresight as an Integral Component of DoD Planning Processes

There is much DoD can do to anticipate and prepare in better ways for the effects of accelerating technological change on the future global security environment. Foresight methods, versus forecasting tools, can be important tools for thinking about the future. Forecasting extrapolates predictions, based on identified trends, while foresight is about anticipating the broader range of possibilities that could emerge from developing strategic conditions. The U.S. Government often is behind the curve here: the Cold War's end and rapid technological innovation have diminished the effectiveness of planning approaches that are primarily analytical/reductive/quantitative approaches. These were built for a complicated world, but not a complex one. Today's increasingly complex world requires more synergistic/holistic/creative perspectives, which unfortunately remain relatively rare.[30]

To support more effective foresight, the U.S. Government will need to build or expand its capabilities for assessing technological situational awareness, understanding the potential impacts of technological developments on militaries and societies, and incorporating these insights broadly into strategic planning. It will also require outreach and coordination well beyond DoD—to other Federal agencies, the private sector, and international actors. There is no single answer to these challenges—some activities should examine new technologies, some, nonmaterial ways of using existing systems more effectively. Some should look at generational

[30] Thanks to our colleagues Neyla Arnas and Josh Kerbel for these insights.

change, some at structures and incentives. Innovation needs to be addressed across the dimensions of people, processes, organizations, and technology. While these efforts will not be simple, the eventual cost of not developing these capabilities could be catastrophic.

Elements of the above capabilities do exist in DoD and other agencies; however, they are often isolated, incomplete, episodic, and poorly accounted for in planning processes. What is needed is a persistent, pervasive, and rigorous set of activities that are institutionalized and valued by DoD leadership. There are several recommendations below to enhance these capabilities.

- *Enhance Horizon-Scanning Activities for Emerging Technology:* Technological horizon-scanning activities are critical to identifying ST&E developments globally and assessing their potential consequences. Such activities exist to some extent within DoD, for example within the Technical Intelligence Office of The Assistant Secretary of Defense for Research and Engineering (ASD(R&E)), and also are addressed by occasional studies of the Defense Science Board (DSB) and other periodic assessments, such as the National Intelligence Council's (NIC) Global Trends studies. However, the accelerating pace of technological change and the increasing globalization of ST&E require that such horizon-scanning efforts be continuous, more extensive, and more in depth.

  To enhance global situational awareness of emerging technology developments, DoD should consider a number of organizational and policy actions to enhance its capabilities. The recent DSB 2030 study has generally suggested increasing budgets for programs related to monitoring the maturity of technology developments globally.[31] More formal mechanisms should be created that can effectively scan for and synthesize technology developments, as have been proposed in a 2009 National Academy of Sciences[32] study. Such efforts have been implemented within the Singapore[33] government, for example. In a previous CTNSP study,[34] Drs. Coffey and Ramberg proposed funding DoD personnel from defense labs to serve as "brain cells" for monitoring foreign technology developments by attending conferences and developing professional relationships with foreign scientists in targeted areas, essentially developing enhanced Human Intelligence (HUMINT) for foreign scientific and technological developments.

  A particularly effective and efficient strategy for horizon-scanning can be the development or use of existing online data mining or synthesis platforms. These platforms include collective intelligence environments such as The Millennium Project,[35] prediction markets such as SciCast[36] or Longbets,[37] online Delphi environments such as TechCast,[38] and ongoing collaborative environments such as Intellipedia.[39] While some of these environments are used in limited ways by DoD, there should be a more centralized, thorough, and institutionalized capability to harvest insights from these increasingly powerful sources.

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31 See http://www.defenseinnovationmarketplace.mil/resources/DSB2030-TechnologyInnovationEnablers2030.pdf
32 See: http://www.nap.edu/catalog.php?record_id=12834
33 See: http://www.rsis.edu.sg/cens/publications/conference_reports/RSIS_ICEDTReport_050110.pdf
34 See *Globalization of S&T: Key Challenges Facing DOD*, Timothy Coffey and Steven Ramberg, NDU Defense & Technology Paper Number 91 (2012).
35 See: http://millennium-project.org/
36 See: www.scicast.org
37 See: www.longbets.org
38 See: www.techcastglobal.com
39 See: www.intelink.gov

Finally, DoD should consider creating mechanisms to engage more effectively with the large number of futures and technology policy organizations and experts that have horizon-scanning activities. Creating a virtual community of interest (CoI) to explore emerging technologies and their national security implications would provide a very cost-effective, consensus-based process that could scope technology trends and evaluate potential scenarios. Similarly, extending this CoI to emerging technology and foresight activities in other Federal agencies, for example through the Public Sector Foresight Network, [40] could provide significant benefit at low cost. The knowledge generated by these activities should additionally be captured in synthesis reports that could inform other DoD analysis and strategic planning processes.

- *Improve Estimates of Future Military Capabilities:* To turn technological intelligence into useful information regarding the future security environment, it is important to assess the potential military value of emerging technologies, as well as their effect on other strategic variables. Activities to assess the future military applications of emerging technologies occur periodically and for limited areas, but because of the increasing pace of technology development, an ongoing and broad effort in this area is necessary to avoid technological surprise and to leverage potentially high impact technologies.

  DoD should seek to enhance its ability to forecast new and transformational military capabilities that will arise from emerging technologies and to broadly incorporate or respond to them. A number of publications at CTNSP have explored the effectiveness of past DoD technology forecasting efforts and also proposed some improvements.[41] The DSB 2030 study has recommended funding conceptual application studies to explore these areas, as well as funding red-teaming and experimentation activities. The NextTech project,[42] funded by the Office of the Secretary of Defense's (OSD) Rapid Reaction Technology Office, is an excellent example of a study that incorporated a broad range of policy, legal, and societal factors in examining potential future effects of emerging technology and should serve as a model for other efforts. The U.S. Army's "Mad Scientist" workshops[43] were also an effective means of exploring the future destructive use of emerging technology, in particular by non-state actors, and should be replicated. Other mechanisms such as online gaming, for example, the Massively Multiplayer Online Wargame Leveraging the Internet[44] (MMOWGLI), could provide a very effective, tailorable, and low-cost crowdsourcing environment to explore future military capabilities and potential future doctrine.

  Because of the accelerating rate of technological change and its increasingly broad impacts, the common approach of occasional studies in limited areas is unlikely to provide effective foresight for DoD on future military capabilities available to itself or its adversaries. Therefore, DoD should consider funding or creating a center devoted to developing foresight about how emerging technology could impact national and international security. This center should engage in outreach to the entire national security ST&E and policy community, as

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[40] See: www.altfutures.org/psfn

[41] See CTNSP Defense and Technology Papers No. 71, 73, and 95, available at: http://ctnsp.dodlive.mil/category/publications/defense-technology-papers/

[42] For a summary report about the NexTech project, see: www.cnas.org/files/documents/publications/CNAS_Gamechangers_BrimleyFitzGeraldSayler_0.pdf

[43] E.g., see: www.wired.com/2009/01/armys-mad-scien/

[44] See: https://portal.mmowgli.nps.edu/

well as the private sector, to serve the role of an integrator and synthesizer of a wide range of information in these areas, and the outputs of this center should be crafted to inform a range of DoD planning and budgeting activities.

- *Incorporate Foresight into DoD Strategic Planning Processes:* DoD's present approach to strategic planning tends to be episodic—quadrennial defense reviews, once-per-administration National Security Strategies, studies leading to occasional executive orders, and the like. The pace of change outlined in this study suggests that this is far too infrequent. There are other models, such as in Singapore,[45] where foresight is routinely and effectively incorporated into governmental processes and developments. Although their focus is well beyond ST&E, similar approaches aimed at *anticipatory governance,* [46] which incorporate continuous feedback loops, not only can greatly reduce the likelihood of technological (and other) surprise but also can improve U.S. government efforts to be proactive. DoD would not only benefit from such a paradigm but also could also take the lead in promoting such approaches across the U.S. Government.

  Developing such an overarching governance framework will require many organizational and cultural changes, but there are a number of steps that could begin this process. The DSB 2030 study has recommended exploring mechanisms whereby senior DoD leadership can be alerted to emerging technology capabilities that could have significant impact. The Center for a New American Security (CNAS) report on the NexTech project has recommended the creation of a White House Interagency Working Group on Emerging Technology and National Security. Another potential option is to create a function at the National Security Council that evaluates national security impacts of rapidly emerging technology areas and potential threats. In terms of planning, a significant advance would be to begin building potential future technology capabilities into DoD's long-range planning scenarios. More fully leveraging the work of North Atlantic Treaty Organization's (NATO) long-term futures program[47] and its European collaborators would be an effective step as well. These actions would increase the likelihood that the knowledge generated by the horizon-scanning and foresight activities discussed previously would be effectively utilized by DoD to anticipate the future global security environment.

- *Build Whole-of-Government/Whole-of-Society Efforts:* Accelerating technological change will affect all of global society across many areas, and DoD is not equipped to understand fully or deal with these ramifications by itself. It must be proactive in reaching out to and coordinating with the rest of the Federal Government to monitor, plan for, and prepare responses to profound change and potential threats to the nation. A Whole-of-Government (WoG) mindset, indeed Whole-of-Society (WoS), will be increasingly important. While WoG approaches are difficult, there has been some success at formulating conceptual frameworks and developing appropriate mechanisms.

  DoD could take a number of actions in the near future to enhance WoG activities to prepare for the future security environment. As in other sectors, ICT can be a broad and cost-

[45] Singapore Centre for Strategic Futures (www.csf.sg/) and Risk Assessment Horizon Scanning (RAHS) (www.**rahs**.gov.sg/)

[46] *Anticipatory Governance: Practical Upgrades*, Leon Fuerth, October 2012, see: http://www.wilsoncenter.org/sites/default/files/Anticipatory_Governance_Practical_Upgrades.pdf

[47] See: www.act.nato.int/futures-work

effective tool, for example in developing collaborative spaces across agencies on specific topic areas. The report on anticipatory governance referenced above outlines a systematic framework and specific recommendations for using foresight and continuous adaptation across Federal agencies to coordinate planning and resources. Project Horizon,[48] conducted in 2006–2007, provides an excellent example of WoG strategic course-of-action planning based on future world scenarios and should be repeated periodically. Additionally, enhanced engagement with international futures and strategic planning activities, such as the Global Futures Forum and the Organisation for Economic Co-operation and Development (OECD) futures program,[49] would be highly beneficial to DoD for providing global perspective at low cost. While full implementation of some of the actions above will require the authority of the White House, DoD can provide strong leadership and a focus on the future international security environment.

2.1.2 ST&E Capacity as a Strategic Variable (GeoInnovation)

In a future environment where advanced technologies underpin militaries, economies, and societies, the capacity to create and adopt new technologies will become as important as other strategic resources, such as energy or population. Some countries have considered ST&E capabilities or technology commercialization infrastructure as key national resources, but they are rare. Today, as ST&E becomes increasingly globalized, many nations are racing to develop these resources and there is an increasingly intense competition for talent, capital, intellectual property, and infrastructure. These elements are key to the process of technological development and are strong indicators of the future technological sophistication and competitiveness of a nation or region. Yet no formalized framework exists to study these factors as a global resource or their effects on the future national security environment.

An analytic framework needs to be developed for a new key strategic variable, namely, the study of how ST&E assets, commercialization resources, and technology adoption capacities are distributed globally, and how they may affect the economic and global security environment in the future. Analogous to the study of geopolitics, this variable could be termed *GeoInnovation*. The factors contributing to GeoInnovation ultimately enhance the diplomatic, information, military, and economic (DIME) levers of national power by underpinning the future economic, military, and political power of a nation. GeoInnovation factors, however, are leading indicators (by years or even decades) as they reflect the future capacity to develop and deploy technological innovations.[50]

A number of existing resources could inform a more integrated framework for GeoInnovation. A 2006 study by Rand[51] addressed in depth the development of emerging technologies, their potential impact, and the likelihood of various countries being able to develop them and is a good model for future studies. The NIC's Global Trends assessments[52] also deal with aspects of how technologies and technological capacities of countries may affect the future international

[48] See interim report: http://www.osif.us/images/Project_Horizon_Progress_Report.pdf
[49] See: http://www.prospective-foresight.com/spip.php?article547
[50] GeoInnovation can build on Innovation Theory, which stresses that the holistic flow of technology and information among people, enterprises and institutions is key to the innovative process on the national or regional level. For example, see the OECD publication: http://www.oecd.org/science/inno/2101733.pdf
[51] See: http://www.rand.org/pubs/technical_reports/TR303.html
[52] See the homepage: http://www.dni.gov/index.php/about/organization/national-intelligence-council-global-trends

security environment. A recent study by the National Academies of Science[53] discussed the national S&T strategies of six major nations and their potential implications for future U.S. national security. Private sector analytic firms also provide analyses of the technological capacity of various regions and nations, such as Cientifica's adoption and commercialization index[54] for different countries. Numerous other sources of data are also available, such as the National Science Foundation's (NSF) Science and Engineering Indicators and OECD economic data, which can form the basis of an initial global assessment of GeoInnovation.

The recommendation is that DoD should consider funding a major study to assess the usefulness of a GeoInnovation analytic framework, the resources that would be required, and how this knowledge and insight could be directly utilized within medium- and long-term strategic planning and budgeting processes.

2.1.3 International Technology Governance and Standards Bodies

The development, commercialization, and adoption of new technologies depend critically on technology standards developed by international bodies, such as the International Organization for Standardization (ISO).[55] Similarly, the governance of global technological infrastructure also increasingly depends on a number of international bodies, such as the International Telecommunications Union (ITU),[56] the Internet Corporation for Assigned Names and Numbers (ICANN), [57] and the World Conference on International Telecommunications (WCIT).[58] The activities of these organizations can deeply affect future technology development, markets, economies, national security, and safety and privacy issues, among other areas. In recent years, the United States has become increasingly detached from the activities of many of these bodies. It represents a disturbing trend at a time when critical issues about some emerging technology areas are being decided. [59] This is potentially a serious threat to future U.S. economic and national security, and in fact other countries are increasingly taking advantage of this lack of U.S. engagement.

Particularly important areas that are in rapid flux include Internet governance, standards for nanomaterials and their safety, international standards for biofuels, safety of synthetic biology, and governance of domestic and military use of autonomous robotic systems. A number of organizations are involved in policy development for national and international governance of emerging technologies and can serve as a resource.[60,61,62]

[53] See: http://www.nap.edu/openbook.php?record_id=12920&page=35
[54] See: http://www.cientifica.com/wp-content/uploads/downloads/2012/10/EmTech-Index-2012.pdf
[55] See: http://www.iso.org/iso/home.html
[56] See: http://www.itu.int
[57] See: http://www.icann.org/
[58] See: http://www.internetsociety.org/wcit
[59] See, for example, Nigel Cameron's June 10, 2014 C-PET (Center for Policy on Emerging Technologies) conversation with Sally Wentworth, Vice President for Global Policy Development at the Internet Society (ISOC), on the future of Internet governance. She reviews the evolution of Internet governance from WSIS 2003/5 through WCIT and Net Mundo and notes that the United States' "multi-stakeholder" approach to Internet governance is not finding acceptance. She sees a greater need for innovation and for the ability of net users to be engaged in decisionmaking. http://www.c-pet.org/wp-content/uploads/2013/03/Sally-Wentworth-June-10th.mp3
[60] See: http://www.oecd.org/science/sci-tech/meetingglobalchallengesthroughbettergovernanceinternationalco-operationinsciencetechnologyandinnovation.htm
[61] See http://belfercenter.ksg.harvard.edu/publication/20463/technology_governance_20.html

The United States must recognize that the development, deployment, and management of advanced technologies and critical infrastructures are key components of economic and national security. Moreover, this security is being increasingly threatened not only by the globalization of technological resources but also by proactive strategies by particular countries to increase their influence via these channels. DoD leaders should work, in concert with other agencies such as the Departments of State and Commerce, to craft new policies and strategies to engage more effectively with international technology bodies and lobby for positive U.S. outcomes. DoD should consider advocating for an interagency working group to develop such unified cross-agency efforts, which will also require outreach to U.S. private sector entities.

2.1.4 Framework for Enhanced Collaboration With the Private Sector

Most technological innovation and deployment occurs outside of the Federal Government, and DoD activities represent an even smaller fraction of the national innovation enterprise. As ST&E becomes increasingly globalized, and U.S. Federal budgets potentially remain austere, DoD will find itself increasingly challenged to marshal the resources necessary to maintain technological leadership. An effective strategy, however, is to leverage the resources of other Federal agencies, and in particular, the private sector. Public-Private Partnerships (PPP) and Public-Private Cooperation (PPC) represent a range of mechanisms that have been used in the past by Federal, state, and local governments to share goals and resources to achieve mutually beneficial outcomes. DoD has developed numerous PPPs in the past; however, its efforts to do so are often hampered by legal, policy, organizational, and contractual restrictions. The U.S. Agency for International Development (USAID) typically is much more flexible the DoD, and their migration to "v4" of PPP based on shared values with private sector entities represents a sophisticated and effective approach. The key point is that DoD must think strategically about what resources it can and should use for PPPs, and it must evolve new organizing principles for partnering with the private sector to make their engagements with DoD easier and more attractive.

DoD is already taking proactive measures to improve how it develops PPPs and PPCs. An April 25, 2013, DoD memo[63] emphasizes the importance of PPPs and gives guidance on authorities and procedure. There is also currently a DoD Working Group on PPPs that is developing a draft DoD Instruction document to flesh out the policy and legal framework for future PPPs. This is a very positive step, but DoD needs to think broadly about a variety of different organizational models that have been used in the Federal Government for PPPs over decades, particularly in the ST&E and commercialization arenas. In the emerging technology area, models such as the Departments of Energy and Commerce shared user facilities are quite valuable, allowing a wide range of public and private sector entities to access rare or expensive scientific equipment and infrastructure and to collaborate.

A considerable body of knowledge and precedence already exists on PPPs and PPCs. A 2012 study by the Defense Business Board[64] made a range of recommendations about PPPs in DoD.

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[62] For an overview of many international technology governance organizations, see http://www.issp.uottawa.ca/eng/pdf/Governance_of_Emerging_Technologies.pdf

[63] See http://www.defensecommunities.org/wp-content/uploads/2011/01/OSD004391-13-RES.pdf

[64] See http://dbb.defense.gov/Portals/35/Documents/Reports/2012/FY12-4_Public_Private_Collaboration_in_the_Department_of_Defense_2012-7.pdf

The Council on Competitiveness has also published a useful summary[65] of different models for PPPs. The National Council on Public-Private Partnerships[66] is an important resource. There is also a significant body of academic literature on PPPs as drivers of ST&E, innovation, and economic growth.[67] The Department of Homeland Security (DHS) has also done considerable work on developing innovative new models for PPPs.[68]

A 2012 CTNSP report[69] on PPPs and PPCs studied some of the current policy and organizational challenges for DoD and made a number of recommendations. It concluded that DoD should (1) create a flexible, unified policy/legal/contractual framework to allow a wider range of PPP and PPC activities beyond what is currently available; (2) develop a "toolbox" of PPP models and contractual templates that is standardized, so that new ones can be implemented relatively easily; (3) in terms of ST&E, expand and streamline contracting mechanisms for funding research, commercialization, and collaboration with private sector partners; and (4) create positions or offices in DoD to coordinate PPP and PPCs across the department, with other agencies, and with nongovernmental partners.

One of the most fruitful avenues for DoD for partnering with the private sector is to engage with regional, state, and local (RSL) ST&E and commercialization initiatives. In the last decade, many states and regional authorities have significantly increased funding and resources for research, commercialization, and technology workforce development to foster high-tech economic growth. RSL initiatives are very flexible in that they can mix resources from Federal, state, corporate, and philanthropic organizations, and they are also much more closely engaged with businesses, universities, and infrastructure providers in their locality. They also have a number of umbrella organizations that develop policy and provide networking opportunities across the United States, such as the State Science and Technology Institute.[70] However, a 2012 policy study about RSL initiatives engaged with development of emerging technologies [71] concluded that RSL initiatives face significant hurdles when attempting to partner with the Federal Government. These include opaqueness of the landscape of the Federal bureaucracy, an uncertain regulatory environment, the amount of time and resources necessary to contract with agencies, difficulties negotiating shared goals, and poor communication and response from their Federal counterparts.

The recommendation is that DoD should seek to develop better policies and partnering mechanisms to take fuller advantage of RSL resources, making full use of the authorities granted to DoD by Section 331 of the 2013 National Defense Authorization Act, since these RSL initiatives will be increasingly important drivers of technological innovation within the United States.

2.1.5 Expanding Privacy Issues

As ICT continue to permeate every aspect of society, it is becoming increasingly difficult for anyone to remain anonymous or undetected. In particular, sensitive personal information can

[65] See http://www.compete.org/images/uploads/File/PDF%20Files/AEMC_Part_PPP_Summary_FINAL.pdf
[66] See http://www.ncppp.org/
[67] Fe example, see: http://www.wipo.int/export/sites/www/econ_stat/en/economics/gii/pdf/chapter2.pdf
[68] See https://www.dhs.gov/xlibrary/assets/st_innovative_public_private_partnerships_0710_version_2.pdf
[69] See http://ctnsp.dodlive.mil/files/2013/07/DH-074.pdf
[70] See www.sst.org
[71] See http://www.nano.gov/node/1020

now be mined from readily available online sources, and social media provides a particularly porous avenue for information flow. [72] Access to such information can be particularly problematic for DoD, quite apart from the need to protect its secure networks and databases. Information available about DoD personnel and their activities in private life are a new vulnerability that could compromise national security concerns. Such sources include information citizens voluntarily share about themselves (e.g., via social media); actions that commercial firms take with that information (location-based services and the tracking of cell phone externals); malicious and criminal activities (hacking and ID theft); financial and marketing information; and soon, data available through common household devices, as the IoT expands its reach.

DoD's response to information security has often been to limit the use of advanced ICT severely. This not only reduces the efficiency and flexibility of DoD personnel but also is no longer an effective security paradigm in an increasingly connected world. Therefore, DoD needs to establish new policy positions and procedures proactively on privacy issues. In particular, effective policies need to be established on Personally Identifiable Information (PII) to determine the Department's ability to make use of information from social media in domestic contingencies.

A number of ICT companies such as Google are developing new concepts for security that involve synergetic combinations of technological solutions with better processes and practices, which should be examined by DoD.

The recommendation is that DoD should establish a program or working group, engaging with Federal and private sector experts, to develop a new paradigm for digital security that would seek to maximize both flexibility and privacy. An example is the privacy rules that have been established through open source community engagement by Wikipedia. DoD must also begin to change its culture to recognize that information leaks will be increasingly commonplace and, in fact, inevitable. Even while continuing to try to protect information responsibly, more attention needs to be paid to resilience when leaks occur and contingency plans to address the release of particularly sensitive information.

2.1.6 Impacts of Emerging Technologies on the Present and Future DoD Workforce

The information revolution and ICT, as well as AI and cognitive science, are creating a wide range of transformational tools for education, training, and the future workforce. They are enabling a lifelong, recruitment-to-retirement, innovative learning environment that supports the delivery of content at the point of need. Some argue that the nature of work itself may change dramatically; others predict that these technologies will create inequalities and social stress. In any case, future generations of DoD personnel will have a different mindset and different skills than in the past. DoD will need to understand how to leverage these capabilities and adapt to new norms of behavior and workplace paradigms. It must also begin to leverage these technologies to create new modes of education and training (E&T) that are appropriate for the information age.[73] If it does not, DoD will be at an increasing competitive disadvantage in attracting the best talent from the larger U.S. workforce.

[72] See the DoD social media hub for current guidelines: http://www.defense.gov/socialmedia/.

[73] See, for example: http://www.emergingedtech.com/2014/04/imaging-the-classroom-of-2016-empowered-by-wearable-technology/.

The impact of emerging technologies on the present and future workforce[74] can be viewed from two perspectives: (1) preparing individuals with the competencies that they will need for future work and (2) addressing the revolutionary changes that are needed in the delivery and consumption of teaching and learning to meet future needs.

A number of very important policy questions for DoD arise in this area. With the rapid changes occurring in technology, how does DoD prepare a workforce for technologies and skills that have yet to be discovered? What enduring skills transcend and apply across new technology developments and needs for the force? How does DoD compete for and support those positioned with these skills needed for the future? How does DoD prepare and transition the current force into developing these future skill requirements that are already emerging? Many of these questions are only beginning to be addressed in the fields of training, education, and foresight.

Organizations preparing their workforce are being driven to change delivery systems, pedagogical approaches, and certification practices. The current E&T systems, including DoD's, have been slow to move out of a static physical classroom environment that uses an industrial approach of teaching everyone the same thing at the same time. The revolutions in information and computer technologies are driving education and training into a personalized learning approach supported by big data analytics. Continual learning will be a requirement for success. Attaining and assessing competencies will not depend on the courses, workshops, or programs the person has attended; an individual's ability to do the tasks required by a job will demonstrate competency. Mentoring, apprenticeships, experiential learning, and communities of interest will become increasingly important for ongoing learning support. The roles of educators and trainers will transition from information delivery agents to facilitators and guides.

DoD needs to begin to organize its E&T efforts to meet this revolution. It should develop programs and working groups to craft strategies for transitioning current E&T doctrine into a new paradigm of innovative, continuous learning that optimizes resources and outcomes. Moreover, it should institutionalize these processes so DoD's E&T activities continually evolve as new technologies and best practices and organizational structures evolve.

2.1.7 Future Defense Industrial and Technology Base

One of the most important aspects of the BRINE areas is their profound impact on new industrial and manufacturing technologies. These include a range of new paradigms, such as IT-enabled smart manufacturing, additive manufacturing, nano-manufacturing, biomanufacturing, and crowdsourcing. Many experts think they will fundamentally re-make the global economy and greatly increase the sophistication of all manufactured goods while improving efficiency and lowering costs.[75] Moreover, such transformational methods motivate, and require, increasing investments in ST&E and commercialization resources, resulting in a "virtuous cycle" of innovation.

The United States, however, is now being severely challenged in the development of advanced industrial and manufacturing capabilities. Many countries are also investing significant resources in research and infrastructure in hopes of capturing market segments for novel products from these evolving capabilities. Much more worrisome is the increasing rate of other nations' acquisition of U.S. technology through concerted campaigns. China, for example, has built a

[74] This subsequent discussion was contributed by Dr. Paulette Robinson, CTNSP, NDU; RobinsonP@ndu.edu.
[75] See, for example: http://www.atlanticcouncil.org/blogs/futuresource/an-emerging-third-industrial-revolution

large government enterprise aimed at acquiring and importing U.S. technology by a wide range of means, some of them questionable or clandestine.[76] Russia is using large capital resources to acquire intellectual property and small high-tech businesses, in aggressive ways—often when these companies are most vulnerable financially. Korea, Japan, and other nations have repeatedly engaged in "dumping" of high-tech products to kill off U.S. competition. Negative factors in the United States, such as flat research budgets, the complexity of government contracting, an uncertain regulatory environment, and an insufficient science, technology, engineering, and mathematics or STEM-trained workforce are also accelerating the offshoring of companies with the most advanced technologies. Many technology policy professionals believe that the loss of high-tech manufacturing is a prelude to the loss of national commercialization capabilities and, eventually, degradation of the national ST&E enterprise.

The U.S. military could be highly vulnerable to these trends. The loss of domestic manufacturing capability for cutting-edge technologies means the United States may increasingly need to rely on foreign sources for advanced weapons systems and other critical components, potentially creating serious dependencies. Global supply chain vulnerabilities are already a significant concern, for example, from potential embedded "kill switches," and these are likely to worsen. The loss of advanced manufacturing also enhances tech transfer to foreign nations and helps build their ST&E base, which accelerates the loss of U.S. talent and capital. This loss of technological preeminence by the United States would result in a fundamental diminishing of national power.

Solving these problems will be hard, in part because of the complex political, economic, and international factors that come into play. It is also beyond the scope of any one Federal agency. However, DoD arguably will be the Federal component most significantly affected by the loss of future U.S. technological preeminence, and should take a leading role to ensure that commercialization activities for critical emerging technologies are fostered domestically. This will require a broad set of activities to address the innovation ecosystems that generate advanced industrial and manufacturing capabilities. These could include the following: increasing funding for DoD ManTech[77] programs; increased partnering with other agencies, such as Department of Commerce's i6 Challenge program[78]; increased engagement with the PPPs being created by the Advanced Manufacturing Partnership[79] under the White House and similar initiatives; DoD's use of its power as a first adopter and limited-run consumer on high importance technology products; development of novel capitalization programs,[80] perhaps similar to In-Q-Tel[81] and DeVenCI;[82] policies or mechanisms to help protect small technology businesses with critical emerging technology products from predatory foreign business practices; and increased engagement with high-tech RSL[83] research and commercialization initiatives. These actions will require a holistic

[76] On 19 May 2014, the U.S. Justice Department filed the first charges ever for stealing industrial secrets via cyber hacking. The defendants are five Chinese PLA officers. See http://www.fbi.gov/pittsburgh/press-releases/2014/u.s.-charges-five-chinese-military-hackers-with-cyber-espionage-against-u.s.-corporations-and-a-labor-organization-for-commercial-advantage
[77] See https://www.dodmantech.com/
[78] See http://www.eda.gov/challenges/i6/
[79] See http://www.manufacturing.gov/amp.html
[80] See the NDU Defense Horizons Report #71: http://inss.dodlive.mil/files/2012/09/DH-71.pdf
[81] See https://www.iqt.org/
[82] For an overview, see http://www.reuters.com/article/2011/10/14/venture-pentagon-idUSN1E79C21O20111014
[83] See the State Science and Technology Institute for extensive information on these resources: http://ssti.org/
DeVenCI is the Defense Venture Capital Initiative

approach by DoD and other agency partners that involves policy, acquisition, research funding, partnering, educational initiatives, and perhaps legislative proposals for financial and international issues.

2.2 Technology-Specific Areas

2.2.1 ICT and Cyberspace

Cyberspace and all aspects of ICT continue to expand and evolve very rapidly, and even near-term future capabilities will be difficult to predict. As a military domain, cyberspace is still poorly understood and lacks a coherent theory for sense-making. There are, however, a number of clear trends that can serve as organizing principles for policymaking or planning. Existing and emerging vulnerabilities clearly need to be addressed.

Whether DoD likes it or not, the agency will be increasingly affected by trends in cyberspace. It will be impossible for its personnel and systems to function without some interface with or reliance on domestic or global infrastructure. Thus far, DoD has been increasingly challenged by rapid developments in these open systems and has suffered due to increasing vulnerabilities and slow adaptation. However, an extensive array of cyberspace capabilities is being deployed to make the Department more proactive, agile, and creative in anticipating and mitigating potential threats and vulnerabilities, since these will only increase, and isolation from cyberspace networks is no longer an option. DoD must focus on organizational, cultural, and process adaptation to solve many of these problems, rather than only strictly technological solutions. Several recommendations are below for some of the most critical issues.

- *Enhance Security of Critical Infrastructure and Industrial Control Systems* Critical infrastructure systems throughout the United States are rapidly implementing automated industrial control systems (ICS) that communicate via cyberspace, and with more and more wireless pathways as well. Few of these systems have effective security in place, and numerous policy reports have brought attention to this serious vulnerability in recent years.[84] DoD systems and facilities rely on such critical infrastructure to a surprising degree, not only for large scale resources (e.g., electric power, telecoms) but also for small-scale support (e.g., environmental controls in buildings). Cyber attacks on and through these systems can not only result in disruption of services but also be used in novel ways, such as surveillance through thermostats or maintenance control systems.

  DHS has recently adopted the term operational technology (OT) to refer to the more general class of online control systems now available. These are defined as, programmable systems or devices that interact with the physical environment (or manage devices that interact with the physical environment). Examples include industrial control systems, building management systems, fire control systems, and physical access control mechanisms. With new standards and off-the-shelf technologies now available for IoT devices, OTs are expanding very rapidly and are a very significant security uncertainty. Supply chain security also is a critical element of infrastructure protection.

  DoD has already taken several steps to begin understanding and addressing these vulnerabilities, such as its recent policy on the Cybersecurity[85] and Risk Management

[84] For example, see http://asymmetricthreat.net/docs/asymmetric_threat_5_paper.pdf
[85] See http://www.dtic.mil/whs/directives/corres/pdf/850001_2014.pdf

Framework[86] and a March 19, 2014, memo from the Office of the Under Secretary of Defense Installations and Environment (DUSD(I&E)) on Real-Property Related ICS. It is also beginning to leverage resources of the Department of Homeland Security's ICS Cyber Emergency Response Team (ICS-CERT) and some of their security products and has also established working groups or is participating in interagency working groups on related subjects. A February 2014 report to Congress gives an extensive overview of these current efforts.[87] However, DoD must increase the priority level of OT security and continue to raise awareness of potential vulnerabilities across its enterprises. DoD should develop additional policies, operational procedures, and even new technologies that are specific to securing OT systems and develop the framework for integrating OT security with private sector providers.

- *Organize Command Structures to Optimize Cyber Assets*: Authority over national cyber assets has evolved for nearly a decade and continues to do so. While the United States struggles with creating a national organizational model to effectively operate in cyberspace, we increasingly lose ground as other countries and non-state actors learn to exploit cyber resources more effectively. DoD has also evolved its organizational structure for cyber assets and operations a number of times and may need to continue to do so in response to the evolving cyber domain. Recently, General Keith Alexander, Commander, U.S. Cyber Command proposed elevating Cyber Command, currently under U.S. Strategic Command (USSTRATCOM), to the level of a full unified combatant command, potentially structured similar to U.S. Special Operations Command (USSOCOM). However, a logical extension of this reorganization may be to create Theater Cyber Commands (for example, a CyberEUR), modeled after the theater special operations commands (TSOC), where it is a sub-unified command of CyberCom but serves a Geographic Combatant Command.[88] A recent CNAS report recommended organizational changes along similar lines.[89] DoD should study the feasibility of this organizational change, which would provide more effective support to regional operations.
- *Understand and Plan for the Asymmetric Aspects of Cyberspace and CyberWar:* DoD relies on, and is vulnerable to, open network infrastructures in cyberspace and other ICT. These networks are increasingly available to most people and organizations globally, and that access is increasingly functional and powerful. Trends in embedded systems and the IoT also mean that vast amounts of data are now being collected from billions of devices and systems globally, and it is increasingly easy to use cyberspace to act on physical systems. Cyberspace is becoming a highly asymmetric environment where even small groups or individuals can operate with some degree of effectiveness against even large organizations[90] by a variety of means. Many of these small groups share information and operational knowledge through user networks and thus have larger effective footprints and resources.[91]

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86 See http://www.dtic.mil/whs/directives/corres/pdf/851001_2014.pdf

87 See 24 February 2014 DoD Report to Armed Services Committees titled "The Threat to the Readiness of Military Installations from Possible Cyberattacks on Civilian Critical Infrastructure."

88 Private communication, Dr. Alex Crowther, CTNSP / NDU.

89 See http://www.cnas.org/digital-theaters#.U2KzEpt16_E

90 See http://flashcritic.com/nsa-cyber-attacks-are-an-asymmetric-warfare-weapon-and-pose-a-significant-threat-facing-the-u-s/

91 For example, see http://www.sans.org/reading-room/whitepapers/attacking/jester-dynamic-lesson-asymmetric-unmanaged-cyber-warfare-33889

DoD needs to develop a much better understanding and appreciation of these developments and develop better policies, doctrine, and resources to effectively operate in such a highly complex and uncertain environment. [92] Technological innovations such as the Joint Information Environment (JIE) [93] will help improve the coherence and agility of DoD's operations in cyberspace and more generally. However, DoD should consider a long-term research program to study the multi-disciplinary, multi-sector, and cross-technological factors that are contributing to this new security domain and develop near-term solutions and long-term strategies that will allow DoD to broadly mitigate risks and operate effectively against a spectrum of actors. Increased use of red-teaming, experimentation, and outreach to the private sector and "hacker" groups would be effective and in many cases require minimal resources.

2.2.2 Energy

Over the last decade, the United States has made an increasing commitment to attaining energy independence, and advanced energy technologies and renewables have been a key component of this strategy. As the largest single consumer of energy in the world, DoD has a major stake in energy security and has been very proactive in funding and deploying both new energy technologies and approaches to energy efficiency. The prospect of up-front demand reduction, whether by design, technology, or processes, offers immediate operational and financial benefits. Moreover, within the last few years, an increasing number of breakthroughs in advanced materials, novel manufacturing technologies, and IT-enabled smart energy systems are creating the possibility of having a range of new economically and operationally viable energy sources available.

At the same time, unconventional oil and gas (UOG) technologies (i.e., "fracking") have created a boom in U.S. domestic oil and gas production. [94] These technologies will have profound consequences for the U.S. economy, as well as geopolitical consequences around the globe. Some experts predict that oil prices may drop very significantly within a few years.

This domestic windfall will likely have a number of unintended consequences. One of these may be a disinvestment in research and commercialization of advanced energy technologies, as they once again become commercially unattractive. Whatever the near-term economics of generation, however, demand reduction remains a place to start. Also, as a policy, the DoD should make a strategic decision to continue its investment in advanced and renewable energy technologies because its unique requirements for expeditionary energy and self-sufficiency will benefit greatly from advancements in solar power, energy harvesting, smart grids, and other emerging energy technologies.

Although not directly within DoD's purview, a strategic policy issue for the United States with regards to the UOG boom will be the possibility of using our domestic energy resources for geopolitical influence, in effect turning the tables on the current major oil producers. While this is a politically sensitive debate at present, one practical change needed to facilitate this strategy is the rescission of the 1975 law[95] banning exports of domestic crude oil. This standpoint is gaining

[92] For example, see http://asymmetricthreat.net/decision_superiority/decision_superiority.shtml
[93] See http://www.disa.mil/About/Our-Work/JIE
[94] For a good overview, see http://www.cfr.org/energy-and-environment/hydraulic-fracturing-fracking/p31559
[95] For a summary, see: http://www.bloomberg.com/quicktake/u-s-crude-oil-export-ban/

political steam currently[96] among economists and oil producers, and a number of influential U.S. senators are now advocating for action.[97]

Emerging technologies can also play a significant role in expeditionary energy requirements for DoD. One significant policy action would be to facilitate negotiations on international standards for biofuels, so DoD could potentially purchase reliable biofuels in theatre when this makes sense operationally. Another would be increased support for the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS), [98] which is exploring the feasibility of cyber-secure smart microgrids with demand-side management and integration of renewable energy and energy storage on military installations for enhanced mission assurance during prolonged outages of commercial power. New nanomaterials are significantly increasing the efficiencies of solar power and will become increasingly useful for onsite energy generation, and other smart materials are also increasing the efficiency of thermal- or mechanical-to-electric energy conversion, making energy harvesting a potentially useful energy source for individual warfighters. Wireless electricity also may become operationally useful.

2.2.3 Unmanned and Autonomous Military Systems

Unmanned and autonomous robotic systems are becoming increasingly more capable and intelligent and are starting to be widely deployed in both military and domestic capacities. This has already raised a number of significant legal, policy, ethical, and regulatory concerns. Perhaps the most serious issue is the possibility of robotic systems that can autonomously decide when to take human life. The specter of Kill Bots waging war without human guidance or intervention has already sparked significant political backlash, including a potential United Nations moratorium[99] on autonomous weapons systems. This issue is particularly serious when one considers that in the future, many countries may have the ability to manufacture, relatively cheaply, whole armies of Kill Bots that could autonomously wage war. This is a realistic possibility because today a great deal of cutting-edge research on robotics and autonomous systems is done outside the United States, and much of it is occurring in the private sector, including DIY robotics communities. [100] The prospect of swarming autonomous systems represents a challenge for nearly all current weapon systems, which partly drives the emphasis on DEWs.

DoD needs to monitor these trends closely and engage with the policy, legal, and political debates surrounding these issues. It should also be highly proactive in taking steps to ensure that it is not perceived as creating weapons systems without a "human in the loop." It may be that DoD should publicly self-limit its operational doctrine on the use of such systems to head off public or international backlash to its development of autonomous systems.[101] DoD should also remain ahead of the curve by developing concepts for new roles and missions and developing operational doctrine for forces made up significantly or even entirely of unmanned or autonomous elements.

[96] See http://www.washingtonpost.com/blogs/wonkblog/wp/2014/01/08/u-s-oil-exports-have-been-banned-for-40-years-is-it-time-for-that-to-change/
[97] See http://www.reuters.com/article/2014/04/02/us-usa-energy-murkowski-idUSBREA310QP20140402
[98] See http://energy.sandia.gov/wp/wp-content/gallery/uploads/SPIDERS_Fact_Sheet_2012-1431P.pdf
[99] See http://www.ohchr.org/EN/NewsEvents/Pages/Acallforamoratoriumonthedevelopmentrobots.aspx
[100] See for example: http://diydrones.com/ or http://openrov.com/
[101] 20YY, *op. cit.*

2.2.4 Directed-Energy Weapons

DEWs have been in development since the 1960s, and today they include a number of maturing technologies that project electromagnetic radiation in some capacity, such as laser light. DoD has begun to deploy test versions of a number of different DEWs and plans to begin installing and integrating them into shipboard combat systems within a few years—USS Ponce deployed in 2014 with an operational laser. There still are technical and operational challenges,[102] but when widely deployed, DEWs will be a very disruptive military technology. They will have unique characteristics, such as near-zero flight time, high accuracy, and an effectively infinite magazine, which will require re-thinking basic battlefield tactics and procedures. DoD continues to invest very significantly in these technologies and the research and development, or R&D, programs have thus far proven effective in delivering functional prototypes. They are also on track to scale up power requirements and mitigate many of the outstanding technical hurdles. DEWs will likely benefit from developments in other BRINE technology areas, such as meta-materials and nanotechnology, which could provide novel power sources, targeting, tracking, and beam forming.

To deploy DEW combat capabilities effectively across the Services, a number of policy, programmatic, and organizational issues still need to be addressed.[103] For example, DoD should develop a strategic plan and roadmap for DEWs, such as has been in development by the Naval Directed Energy Steering Group. DoD should also develop a program of record for DEWs to define its acquisition plans, which would help industry focus its development efforts as well. Given the potentially austere future budget environment, it may be wise also for DoD to begin down-selecting from the number of different technologies it currently has under development and integrating the rest into a structured prototyping and experimentation regime. DoD should also accelerate development of new doctrine and tactics for using DEWs effectively in a battlefield capacity, since their unique characteristics will require years of operational development to fully exploit and integrate with existing kinetic weapons systems. Finally, considerable cultural adaptation by personnel will need to occur for weapon systems as unique as DEWs, and DoD should begin to explore education and training capabilities for their assimilation, for example tactical computer simulations.

2.2.5 Biotechnology

Biotechnology is a very broad area that is evolving very rapidly—faster, in many ways, than even ICT.[104] A tremendous amount of funding flows into this area from governments, companies, and venture capitalists, both domestic and international. This research is producing revolutionary devices, designer drugs, green manufacturing processes, and advanced prosthetics, some of which are creating legal, ethical, and even political challenges. Innovations in medicine and biotechnology also are increasingly being driven by tools from the other BRINE areas, in particular ICT and nanotechnology.

The issue space of biotechnology is too large to cover here, but there are a few areas of considerable relevance to DoD technologically that may also prove to have significant policy challenges. These are discussed below.

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[102] See Elihu Zimet and Christopher Mann, *Directed-Energy Weapons—Are We There Yet?* NDU, CTNSP, May 2009, http://ctnsp.dodlive.mil/files/2013/07/DTP-062.jpeg.

[103] For an overview of these issues, see CRS report R41526, available at: https://opencrs.com/document/R41526/.

[104] See Figure B-1.

- *Human Augmentation:* DoD has funded research on technologies to enhance human performance for decades. Today, however, there are a number of technologies that could profoundly alter not just human performance, but human physical, psychological, and cognitive makeup as well.[105] These include personalized (genetic) medicine, tissue and organ regeneration via stem cells, implants such as computer chips and communication devices, robotic prosthetics, direct brain-machine interfaces, and potentially direct brain-brain communications. Many of these will provide significant future capabilities for DoD, on and off the battlefield. However, many will also raise significant policy, legal, and ethical issues, such as the ethics of compromising or changing the integrity of an individual's body or deeply altering an individual's cognitive or decisionmaking processes. In many cases there may be public reactions or legal challenges to these capabilities. A case in point involves the predictive potential of personal medicine, with its implications for personnel assignments and long-term care. DoD should therefore consider establishing multidisciplinary working groups or funding studies or centers ahead of the deployment of particularly novel biotechnology capabilities in these areas.
- *Bioinformatics, Big Data, Digital Health Records:* The application of ICT and large-scale data collection has many powerful advantages for medicine and society,[106] and DoD can leverage these advantages as well. Personalized or genetics-based medicine could greatly improve the effectiveness of treatment and lower a variety of costs. Collection and analysis of large sets of data from many individuals could make patient care more effective and lower cost by correlating variables to improve treatment options (i.e., precision medicine).[107] Monitoring of individuals and populations using sensors, wearable devices, and IoT will provide detection and predictive analytics that can move toward a health maintenance-based, rather than a disease-based medical model, and also enhance operational readiness. However, there will be many risks involved as these systems are implemented, for example, the many ways that digital data or privacy information can be compromised, issues of ownership or of access to the data. These systems will also require new enterprise-level models for the management and exploitation of potentially huge amounts of health related data.

  DoD should continue to pursue these avenues in partnership with large private sector providers, where the most innovative solutions are currently developing.[108] At the same time, DoD will need to enhance its efforts towards information security, cyber security, and the protection of personally identifiable information (PII) as these systems are deployed.

- *Brain Mapping and Cognitive Science*: With recent advances in cognitive science and the creation of major brain mapping initiatives in the United States and other countries, major leaps are on the horizon for deeply understanding and enhancing human cognitive performance. For DoD, these capabilities could greatly improve individual warfighters' ability to assess situational awareness, make decisions, and reduce cognitive load and stress. These advancements can also improve larger scale activities, such as tools for leadership decisionmaking, and the understanding of socio-behavioral dynamics and human geography.

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[105] See Appendix B for a longer discussion.

[106] See http://www.mckinsey.com/insights/health_systems_and_services/the_big-data_revolution_in_us_health_care

[107] See for example: http://healthaffairs.org/blog/2013/02/21/rapid-learning-for-precision-medicine-a-big-data-to-knowledge-bd2k-initiative/

[108] For example: http://www.marketwatch.com/story/ibm-joins-forces-with-epic-to-bid-for-department-of-defense-healthcare-management-systems-modernization-contract-2014-06-10

However, the principal hurdles for DoD, in exploiting these new capabilities, may involve culture, education and training, organizational adaptation, process development, and other human factors. DoD should begin now to plan for the adoption of these new capabilities to maximize their impact as they evolve, as they could be critical enablers for the U.S. military in the future.

- *Synthetic Biology:* Synthetic biology (SynBio) may become one of the most transformational areas of ST&E in the near future. Researchers have recently created cells with DNA composed of non-natural amino acids, opening the door to the potential creation of designer life forms. Moreover, SynBio tools are now available, relatively cheaply, to an expanding DIY community, and research is being pursued commercially in many countries. SynBio has the potential to generate significant tactical, operational, and strategic impacts across a wide range of defense-relevant applications in medicine, human performance, weapons, power and energy, sensors, and high-performance materials, and it should be a priority research, development, and engineering area for DoD.[109] However, this area may soon raise significant legal, ethical, and regulatory issues related to the creation of entirely new biologic entities. The potential for malicious or terror-related activities will also increase as these methods become cheaper and more widespread. One important application that may prove valuable for DoD is its application to biomanufacturing. For example, biomanufacturing processes are performed under ambient conditions, thus enhancing safety in the production of new energetic materials, biofuels, and high-value specialty chemicals and feedstocks. DoD needs to closely monitor this area not only for potential opportunities but also for potential risks and foreign competition.

[109] OSD(R&E) research assessment: Herr, Andrew, *DoD Research and Engineering Technology Assessment: Synthetic Biology*, to be published.

3.0 Conclusions

Accelerating technological change is not just the stuff of science fiction, nor is it relegated only to technology communities. Increasingly it is affecting every aspect of global civilization. It will enable not only profoundly positive advancements for mankind but also new modes of warfighting and tools for malicious behavior. It may also have contradictory effects on the future security environment. For example, while it will likely flatten the world economically, socially, politically, and militarily, it could also increase wealth inequality and social stress. DoD cannot afford to be unprepared for its consequences. The successful countries, organizations, and individuals of the future will be those that can continually sense and adapt to a constantly changing global landscape.

For DoD to remain the world's preeminent military force, it must redefine its culture and organizational processes to become more networked, nimble, and knowledge-based. It must view technological change not only as improvements in capabilities but also as the organic evolution of a new cross-domain environment whose influence will be pervasive.

With the current re-balancing of the U.S. global force posture, there is an opportunity today to explore longer range thinking and alternate future trajectories. DoD leadership should examine more closely the trends and potential consequences of profound technological change and how DoD could shape, and not simply react to, the outcomes. The recommendations discussed in this paper, while not comprehensive, do address important issues that could influence such a process.

Appendix A: Summary of Reports Identifying Key Emerging Technologies

Below are short summaries of several recent reports and statements that cover viewpoints about key emerging technology areas and related issues that might affect future national security.

Excerpt from ASD(R&E) FY13 Budget Testimony[110]

Testimony by Zach Lemnios: "In FY2010, we gathered over 200 scientists, engineers, operators and subject matter experts from across the Department and launched a comprehensive analysis of operational architectures, critical capabilities, and enabling technologies to support the Department's current and future missions. We took a broad look at cross-cutting areas that would have the greatest impact to the Department, even as the Department's New Strategic Guidance was being outlined.

That review resulted in the April 2011 announcement by Secretary Gates that the Department will consider seven S&T areas as key priority areas. These priority areas are supported in the FY 2013 PBR [performance-based remediation] 2013; these investments provide the technical foundation for important future capability options:

- *Cyber S&T:* The focus of cyber S&T is on the development of technologies that enable system resiliency, agility, and mission effectiveness across the spectrum of joint operations. The research also addresses foundations of trust and development of new frameworks to more thoroughly assess cyber-security techniques.
- *Electronic Warfare/Electronic Protection (EW/EP)*: Pervasive advances in commercial and consumer electronics challenge conventional U.S. electronic warfare capabilities. Investments in this area focus on new concepts and technology to protect systems and extend capabilities across the electro-magnetic spectrum.
- *Data-to-Decisions*: The Department relies upon the ability to analyze enormous data sets very quickly. Data-to-Decisions investments focus on investments in automated analysis techniques, text analytics, and user interface techniques to reduce the cycle time and manpower requirements required for analysis of large data sets.
- *Engineered Resilient Systems:* The technically advanced systems our Joint Forces will need in the future must be adaptable to operate in dynamic, and sometimes unpredictable, environments. Research in Engineered Resilient Systems focuses on agile and cost-effective design, development, testing, manufacturing, and fielding of trusted, assured, easily-modified systems.
- *Counter Weapons of Mass Destruction (WMD)*: The Department is focused on cross-cutting research in countering weapons of mass destruction, specifically directed at finding and tracking unsecured fissile material. Research focuses on the development of novel detectors and processing algorithms for increased detection capabilities.
- *Autonomy*: The Department's investments in this area are focused on developing systems that can operate in complex real-world environments. Such systems will augment or substitute for human operators, particularly in hazardous environments, and to conduct missions that are impractical or impossible for humans.

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[110] Available at http://www.defenseinnovationmarketplace.mil/resources/Lemnios_Testimony_2013.pdf.

- *Human Systems*: The goal of Human Systems is to advance the Department's technology capabilities for development of system interfaces and for training of personnel to increase productivity and effectiveness. Training research focuses on realistic, adaptive, and interactive scenarios, and persistent, affordable integrated training. Personnel training research concentrates on human-machine teaming; intelligent, adaptive human aiding; and intuitive interaction.

These are emergent technologies that could form the basis for the next generation of dominant military technologies in the next decade:

- *Synthetic Biology*: Involves modifying living cells (typically bacteria) to produce novel substances, such as biofuels, biosensors, improved vaccines, and high strength materials.
- *Quantum Information Science:* Uses quantum mechanics to perform otherwise intractable numerical calculations, provide ultra-secure communications and solution possibilities to certain important problems, and enable an ability to simulate exotic materials.
    - *Cognitive Neuroscience*: This study of how the brain functions provides a deeper understanding of human learning and decisionmaking, which can lead to improvements of performance under stress and to cures to the effects of war trauma.
    - *Novel Engineered Materials:* Encompasses superconductors, metamaterials, plasmonics, and spintronics, among other materials, that can provide fluid-repellant coatings, yield self-healing composites, improve energy efficiency, improve antennas and detectors, and greatly increase computational capabilities.
    - *Human Behavior Modeling*: Modeling of individuals, groups, and nations is intended to enhance strategic and tactical decisionmaking, improve immersive training and mission rehearsal, and facilitate cross-cultural coalition building.

CNAS Emerging Disruptive Technologies Report[111]

In 2013, CNAS published a report entitled *Game Changers: Disruptive Technology and U.S. Defense Strategy*. This report summarized the results of the NexTech project, which explored emerging disruptive technologies, their potential implications for defense strategy, and their key policy questions. The report highlighted the following technology areas:

- **Additive Manufacturing:** This could fundamentally impact the defense industrial base and the manufacturing process, writ large, by dramatically increasing the pace of moving from prototype to production and by enhancing the flexibility and adaptability of production lines.
- **Autonomous Systems:** Autonomous and semi-autonomous systems have already revolutionized ISR and counterterrorism. In time, autonomous systems could be applied across a broader range of military operations and intelligence activities.
- **Directed Energy:** These technologies have been under development since the 1960s and offer a variety of potentially game-changing applications that could be deployed within existing organizational constructs and concepts of operation.
- **Cyber Capabilities**: With over 2.4 billion individuals online globally, cyber capability is already—and will continue to be—game changing, with rapid increases in Internet usage

[111] *Game Changers: Disruptive Technology and U.S. Defense Strategy*, Center for a New American Security, 2013; available at http://www.cnas.org/files/documents/publications/CNAS_Gamechangers_BrimleyFitzGeraldSayler.pdf.

penetration, software innovation and the existing variety of applications and connected devices.

- **Human Performance Modification (HPM)** : Advances in biology and genetics are opening up a number of possibilities to increase the impact of HPM in ways that present significant opportunity but also pose deep philosophical and moral questions.

One conclusion of the study was that **"**the tremendous potential of these game-changing technologies requires consistent investment and attention by defense policymakers as well as more robust collaboration between DOD and leading-edge innovators in the commercial sector."

The Intelligence National Security Alliance (INSA) Emerging Science and Technology Study[112]

In April of 2013, INSA published a report entitled *Emerging Science and Technologies: Securing the Nation through Discovery and Innovation*. The study's premise was that S&T investments have historically provided for a significant intelligence and national security advantage for the United States, but that increased global competition threatens that long-term leadership. It therefore recommended increased investments in key research areas, organized by technical application area:

Technical Collection Research Recommendations:

1. New Generation Sensors
2. Energy Harvesting
3. Bio-Mimicry
4. The Internet of Nature

Communications and Sharing Intelligence Research Recommendations:

1. Swarm Technologies and Communications
2. Holographic Telepresence
3. Advanced Materials for Computing
4. Bio-Inspired Computing

HUMINT Collections and Operations Research Recommendations:

1. Big Data Knowledge Discovery for Asset Identification
2. Countering Asymmetric ISR for HUMINT Signature Reduction
3. Behavioral Biometrics
4. Bacterial Steganography

Intelligence Analysis Research Recommendations:

1. Derivation of Knowledge from Data
2. Human-Inspired Big Data Access Strategies
3. Activity Based Intelligence and Predictive Analytics

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[112] Emerging Science and Technology: Securing the Nation through Discovery and Innovation, Intelligence and National Security Alliance, 2013; Available at http://www.cnas.org/files/documents/publications/CNAS_Gamechangers_BrimleyFitzGeraldSayler.pdf

Protection of the Intelligence Enterprise Research Recommendations:

1. Quantum Computing and Associated Technologies
2. Self-Protecting Data
3. Data Authentication

The study further noted: "We believe that additional interest and emphasis in these recommended research areas has the potential to revolutionize the intelligence capabilities of our nation and enhance U.S. leadership in S&T."

Atlantic Council 2030 Report on the Technology Revolution[113]

In 2013, The Atlantic Council published a report entitled *Envisioning 2030: U.S. Strategy for the Coming Technology Revolution*, in which was covered a number of emerging transformational technologies, and a proposed strategy for harnessing these technological innovations to help the United States maintain leadership in the coming decades. It organized these recommendations into three broad areas (Manufacturing, Energy, and Cities) and identified several emerging or disruptive technologies in each area which should be priorities. These were as follows:

Manufacturing:

1. Synthetic Biology and Biomanufacturing
2. 3D and 4D Printing
3. Robotics, including AI and unmanned vehicles

Energy:

1. Hydraulic Fracking, especially technologies for making it environmentally friendly
2. Smart Grids

Cities:

1. ICT to create "smart cities" that optimize resources
2. Green Technologies, especially use of engineered bio-organisms

This report also called for a national emphasis on STEM education, and reform of the immigration and visa frameworks to make it easier for U.S. trained foreign scientists and engineers to remain in the United States

The NIC Global Trends 2030 Report[114]

While NIC's future assessments typically address a broad range of issues such as demographics, economics, military, and socio-political trends, they also consider a range of potentially disruptive technologies. The most recent report identified the following four general areas, and specific technologies within those areas:

[113] Envisioning 2030: U.S. Strategy for the Coming Technology Revolution, the Atlantic Council, 2013; Available at http://www.atlanticcouncil.org/publications/reports/envisioning-2030-us-strategy-for-the-coming-technology-revolution

[114] See http://www.dni.gov/files/documents/GlobalTrends_2030.pdf, pp. 83-95.

Information Technologies:

1. Big Data Solutions
2. Social Networking Technologies
3. Smart City Technologies

Robotics:

1. Robotics, especially in manufacturing
2. Autonomous Vehicles
3. Additive Manufacturing

Resource Technologies:

1. Genetically Modified Crops
2. Precision Agriculture
3. Water Management Technologies, especially micro-irrigation
4. Bio-based Energy
5. Solar Energy

Health Technologies:

1. Disease Management, especially through personalized medicine
2. Human Augmentation

DSB Report on Technology and Innovation Enablers for Superiority for 2030[115]

In August of 2013, the Defense Science Board published the final report for its 2012 Summer Study on *Technology and Innovation Enablers for Superiority in 2030*. The study reviewed emerging technologies that will enable the next generation of dominant military capabilities, anticipated to be in development or fielded by 2030. However, the report made a very valuable contribution by organizing technological developments according to desired military capabilities to address potential threats by 2030. These general capability requirements and potential investment opportunities were as follows:

Coping With Parity:

1. Satellite Security
2. Cold Atom Sensing for Navigation and Timing
3. Networks Inherently Self-Defensible to Cyber Attack

Achieving Superiority Through Cost-Imposing Strategies:

1. Conventional, Affordable Effects at Intercontinental Ranges
2. Long Endurance, Autonomous, Networked Unmanned Underwater Vehicles
3. Enhanced Vertical Lift

Achieving Superiority Through Enhancing Force Effectiveness:

1. Radionuclide Power to Lighten the Soldier's Load
2. Warfighter Resilience and Performance
3. Next Generation Training

115 See http://www.defenseinnovationmarketplace.mil/resources/DSB2030-TechnologyInnovationEnablers2030.pdf

Anticipating Surprise:

1. Nuclear Proliferation Prevention
2. Horizon Scanning and Hedging
3. Use of Experimentation to Avoid and Create Surprise

In addition, the study identified a number of disruptive emerging technologies which were high payoff and high risk, but which it did not feel would be mature by 2030:

1. Extreme Prosthetics
2. Bespoke [made-to-order] Materials
3. Universal Energy Approach for Warfighter Systems
4. Global Persistent Surveillance via Distributed Aperture Sensing
5. Thought-based Machine Control
6. Micro Climate Engineering
7. Exploitation of Entanglement Physics
8. Portable Compact Fission for Megawatt Power Levels

CNAS Report on Robotic Warfare[116]

In January of 2014, the Center for a New American Security published a report entitled "20YY: Preparing for War in the Robotic Age". This report proposes that a new warfighting regime is emerging that could see a future "in which guided munitions and battle networking has fully proliferated and unmanned and autonomous systems have become central to combat ..." Also: "The integration of manned and unmanned systems in the armed services will spur profound debates regarding U.S. military roles and missions, the operational concepts necessary to take full advantage of new technologies, and the ethical and moral implications of doing so." It listed a number of technological drivers which are underlying these developments:

1. Cyber Warfare
2. Protected Communications
3. Advanced Computing and Big Data
4. Autonomy
5. Artificial Intelligence
6. Commercial Robotics
7. Miniaturization
8. Additive Manufacturing
9. Small, High Density Power Generation
10. Electric Weapons
11. Human Performance Modification

Additionally, it outlined a number of defense policy issues that these developments will potentially impact:

1. Deterrence
2. Crisis Stability
3. Force Posture
4. Alliances and Partnerships
5. Roles and Missions

[116] See http://www.cnas.org/sites/default/files/publications-pdf/CNAS_20YY_WorkBrimley.pdf

6. Operational Concepts
7. Accelerated Diffusion and Technological Surprise

The report also noted that this may be a particularly different future environment because most technological development in this area is occurring in the private sector, and outside the United States.

Appendix B: The Revolution in Biology, Biotechnology, and Medicine

General Trends: Over the last few decades, biology has experienced as profound a transformation as physics did over a century ago. One principal driver was the discovery and characterization of DNA, which is essentially the genetic blueprint[117] for an organism. With the sequencing of the human genome in 2003, and many other genomes since, real progress is now being made in creating therapies and biotechnologies that manipulate and exploit specific genetic information. Progress is also being made at higher levels of complexity, such as transcriptomics and proteomics, and increasingly towards the detailed understanding and manipulation of the dynamics of cells, tissues, and whole organisms.

Another prime driver of the rapid advances in biology is a far greater use of quantitative methods. Many fields of biology now routinely employ advanced mathematical and computational techniques, and computer modeling holds real promise as a replacement for *in situ* experimentation. The large scale application of information technologies, simulations, and bioinformatics is facilitating rapid advancement in many areas, from disease diagnostics to environmental affects to public health.

A wide range of technologies from other fields is also contributing to the increasingly rapid rate of innovation in biology and biotechnology. For example, nanotechnology is being exploited for advanced sensors, chemical characterization and design, and rapid bioassays. Functionalized materials are also making possible new kinds of implants and prosthetics, biosensors, and direct brain-computer interfaces.

Transformational Technologies: Within these general trends, there are a number of specific technology areas that have significant potential to dramatically alter the future landscape of technology, business, trade, and national security. Development and commercialization of products from these areas will provide high value economic growth in certain sectors, as well as the facilitation of a range of new capabilities, from medicine to public health to the military. These transformational technology areas include:

- *Rapid Characterization and Detection:* The ability to measure, store, and analyze information from and about biological systems is now improving exponentially. One key example is the speed and cost of sequencing DNA, which has improved at an astounding rate over the last decade. Figure B-1 below shows a plot of the cost of sequencing a human-sized genome over the last decade,[118] which has dropped far faster than a comparable Moore's law improvement would predict.

[117] See http://www.biology-online.org/dictionary/Dna
[118] See http://www.genome.gov/sequencingcosts/

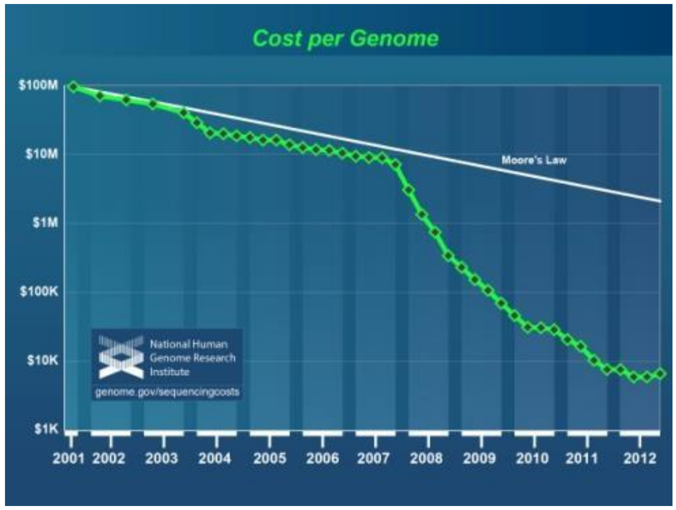

Figure 1: Cost to Sequence a Human-Sized Genome

- Similarly, biochemical detection and characterization is improving dramatically, as increasingly sophisticated biosensors are developed which incorporate biologically sensitive materials, electronic detection and signal processing elements, and external communication capabilities. Integrated "lab on a chip" technologies and massively parallel bioassay methods are increasingly cheap and powerful, improving performance and dropping cost dramatically. The application of nanotechnology and nanomaterials to biosensing is already being developed, and has the potential for extreme sensitivity and specificity,[119] to the point of being able to identify single molecules or a single diseased cell. As size decreases and capability improves, such multifunctional biodevices can increasingly be incorporated in or on living organisms for monitoring or even intervention. For example, the Boston-based company, MC10, is marketing flexible electronics that can be printed on the skin or embedded within the body, to perform complex monitoring functions.[120] Highly specific and reliable biometrics are another near term application. Longer term capabilities could feasibly include a "smart dust" of nanosensors that could be distributed finely over large areas and produce massive amounts of data for environmental, security, or potentially battlespace applications.
- *Genetic Modification of Organisms:* Direct genetic modification of organisms is now a well-established research area (e.g., a range of genetically modified plants are already in use). Genetic modification of insects and animals is increasingly possible and has already been demonstrated in a few instances; however, there are significant biological, cultural, ethical and legal issues with the release of such organisms into an ecosystem. Experiments on altering the genes of individual humans began in 2000, and a number of successful clinical applications have been reported for fertility or genetically related diseases;[121] however, there have been some serious side effects as well. Many believe it is becoming increasingly possible to modify a human's genetic makeup successfully to select for increased physical performance, intelligence, memory, or even appearance. However, such experimentation may

[119] See http://www.nanowerk.com/spotlight/spotid=22137.php
[120] See http://blogs.wsj.com/venturecapital/2012/12/17/are-wearable-flexible-electronics-the-next-big-thing-mc10-says-so/
[121] See http://www.naturalnews.com/036372_genetically_modified_human_babies.html

carry serious risks of harmful side effects to individuals, or even future generations. Genetic engineering of "super bugs" as bioweapons is a near term possibility, and these may already exist.[122] Another hypothetical long-term military application that has been proposed is the engineering of future "super soldiers"; however, major social and ethical hurdles to such experimentation will likely exist in many countries.

- *Personalized Medicine:* With the development of sophisticated chemical and physiological analyses and monitoring technologies, and the ability to cheaply sequence an individual's genome, the possibility of designing individual-specific drugs and therapies will become a real possibility over the next 5 to 10 years. Since treatment of patients by conventional "general" medicine results in millions of adverse reactions each year that waste billions of dollars in health-care costs, personalized medicine will revolutionize many aspects of health care. Such cost savings may benefit the U.S. military greatly. However, others have also hypothesized that these capabilities could also be "weaponized" to attack particular racial or ethnic groups.[123]
- *Replacement of Organs, Limbs, Tissues:* Replacement of organs via artificial electro-mechanical devices is already possible for a wide range of body parts. However, many recent developments which combine tiny sensors, miniature electro-mechanical systems, advanced digital control algorithms, and advanced biomaterials are now revolutionizing the sophistication of such prostheses. For example, in 2012 Swedish researchers successfully tested the first fully implantable, thought-controlled human prosthetic arm,[124] and the U.S. Army is conducting research in this area on cognition and neuro-ergonomics.[125] Reliable artificial lungs, ear and eye implants, and muscles will all likely be commercially available within 5 to 10 years. A much more significant advancement is the use of stem cells for potentially regenerating every human body part. Stem cell research has made tremendous strides in the last decade, and has advanced to the point where there are many existing clinical treatments and a fledgling stem cell engineering industry worldwide[126] with a market value of nearly $90 billion. Applications beyond body part regrowth include rapid drug testing, treatments for fertility and aging, and even growth of biologically inspired circuits for artificial intelligence.
- *Computation and Bioinformatics:* Characterizing biological organisms and systems requires an enormous amount of information that increases dramatically with the level of detail. Information technologies are therefore playing an increasing and critical role in biology and biotechnology. Gene sequencing is an obvious example, which was a major computational hurdle for even a single individual, yet a proposed next step is to sequence the entire U.S. population and perform sophisticated analyses on this database. Bio-informatics is also an important tool in a wide range of other areas, such as molecular biology, drug discovery, and disease correlation in public health. Modeling and simulation are playing an increasingly important role, from molecular dynamics to whole individuals or ecosystems. These areas are all increasingly in need of faster computers and larger memory storage, as well as a range of

[122] See http://abcnews.go.com/Health/story?id=117204&page=1

[123] See http://salempress.com/store/samples/encyclopedia_of_genetics_rev/encyclopedia_of_genetics_rev_biological_weapons.htm

[124] See http://www.gizmag.com/thought-controlled-prosthetic-arm/25216/?utm_source=Gizmag+Subscribers&utm_campaign=ee62cbcbf4-UA-2235360-4&utm_medium=email

[125] See http://www.arl.army.mil/www/default.cfm?page=393

[126] See http://www.wtec.org/SCE/

advanced algorithms and visualization tools. Another important application of ICT to biotechnology is for telemedicine, which includes digital medical records, expert system diagnoses, remote health care, and even robotic surgery. Telemedicine already accounts for almost 15% of health-care applications in the United States and is growing by about 30% per year. As a wide range of biological, environmental, and medical monitoring devices come online, from *in situ* patient devices to supply chain monitoring, real time situational awareness of the public health landscape is becoming a real possibility. Applications to disease outbreaks and WMD events are immediate.

- *Neuroscience/Neurobiology:* The field of neurobiology has undergone very rapid development, with a deeper understanding of the nervous system resulting in applications ranging from "thought controlled" prosthetics and improved detection of physiological and emotional states of humans, to better treatment for various psychological disorders or damage (e.g., Post-Traumatic Stress Disorder, or PTSD). Recently, neuroscientists have proposed a large-scale Brain Activity Mapping [127] project to map the physiological underpinnings of brain activity, a project some have compared to the human genome sequencing in scope and importance, and the Obama Administration has recently added this to the FY2014 budget request.[128] The larger field of neuroscience continues to show rapid progress due to advanced methods such as neural imaging, electrophysiology, and brain-related DNA sequencing, and new fields such as neuro-economics and social neuroscience, which are beginning to understand the physiological origins of human decisionmaking and how humans interact with others and their environment. The above areas all have a wide range of important military applications, from clinical treatment and training, to human performance enhancement, as well as organizational behavior and even applications to counterterrorism.
- *TransHuman Augmentation:* A more radical area of technological development falls within the intellectual movement generally called "transhumanism," basically the belief that human beings could and should fundamentally change their physical beings by enhancing them with transformational technologies.[129] Such futuristic enhancements include eliminating aging, creating super intelligence, synthetically replacing a person's entire body, or digitally uploading their mind. While much of this area is speculation and philosophy, a surprising number of technologies are now developing or are available that are already raising these possibilities.[130] Psychostimulants and cognition enhancing drugs are already available and developing rapidly. Direct implantation of silicon memory and processors into the brain have been successfully demonstrated, as have purely thought controlled devices.[131] These advancements not only have direct military applications, they also could be utilized in clandestine operations or espionage, and potentially even by terrorists.
- *Synthetic Biology:* SynBio is a radical new branch of biology and bioengineering that is making it possible to design an entirely new sequence of DNA, model its properties, chemically produce it, and insert it into an empty cell. The possibility therefore exists to create entirely new organisms that have never existed before, and potentially to give them

[127] See http://www.livescience.com/27721-brain-activity-map-project-launch.html
[128] See http://www.whitehouse.gov/blog/2013/04/02/brain-initiative-challenges-researchers-unlock-mysteries-human-mind?utm_source=040213&utm_medium=topper&utm_campaign=daily
[129] See http://humanityplus.org/
[130] See http://io9.com/5967896/us-spy-agency-predicts-a-very-transhuman-future-by-2030
[131] See http://www.cyberkineticsinc.com/

specialized and exotic properties. Recently, Craig Venter, of the J. Craig Venter Institute, announced that his lab had effectively created a living cell with an entirely new genome,[132] perhpas the world's first synthetic life form. More worrisome, the basic knowledge and equipment for designing, modifying, or producing synthetic DNA is now so cheap and readily available, through open source networks[133] and even from eBay, that a new area of DIY Biology has been born.[134] This has raised deep concerns from a wide variety of groups about the possibility of having potentially thousands of new life forms created by "biohackers" released into the environment, with unforeseen consequences, and there are now serious discussions about developing regulation for Federal oversight.[135] What is clear is that we have already entered uncharted territory in terms of the potential for creation of new pathogens and other bioweapons, which might be leveraged by a range of actors. However, a recent OSD Research and Engineering assessment of current research in the field suggests that SynBio also has great promise for the engineering of synthetic organisms that will be useful or produce inputs for a wide range of defense relevant applications, many for DoD, across medicine, human performance, weapons, sensors, and high-performance materials.[136] These relevant applications include forward manufacture of fuel and pharmaceuticals, active and passive signature management, chemical and biological defense countermeasures, data storage and fusion, lightweight armor, smart coatings and materials, soldier health, and enhanced human performance and training.[137]

National Security Implications: Biology and biotechnology are likely the most rapidly evolving areas of S&T today, and have some of the most profound implications. The breadth and speed of these advances make them difficult to fully assess, although there is potentially much low hanging fruit that the national security community might take advantage of. New technologies and treatments for force protection, health, and medicine will likely be significantly more effective than others and could provide great cost reductions. Advanced artificial prosthetics offer much for treatment of veterans, as well as artificial human augmentation for a variety of tasks and even battlefield use. Bioinformatics and telemedicine also have great promise for reducing the cost of health care and emergency treatment. Genetic modification of organisms and SynBio, while some of the most important new technologies now appearing, may also constitute a grave new threat area, as the difficulty and cost of creating new organisms and bioweapons falls dramatically. The rapid growth in the field of synthetic biology and the potential for it to generate significant tactical, operational, and strategic impacts in a wide range of defense relevant applications, from medicine, to human performance, weapons, sensors, and high-performance materials merit its recognition as a priority research, development, and engineering area for the DoD.

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132 See http://www.dcbar.org/bar-resources/publications/washington-lawyer/articles/may-2012-diy-scientist.cfm

133 See www.DIYbio.org

134 See http://www.openscientist.org/2011/10/tools-of-trade-for-do-it-yourself.html

135 See http://www.dcbar.org/for_lawyers/resources/publications/washington_lawyer/may_2012/DIY_scientist.cfm

136 Herr, *DoD Research and Engineering Technology Assessment: Synthetic Biology*, op.cit.

137 Internal CTNSP report on Synthetic Biology by Dr. James Valdez, james.j.valdes.civ@mail.mil.

Appendix C: The Revolution in Robotics, Artificial Intelligence, and Human Augmentation

General Trends: Robotics is often defined as the development and deployment of automated machines. It has a surprisingly long history; however, today it is reaching the stage where significant numbers of sophisticated robots are being sold commercially for industrial, military, and even domestic use. Robotics involves a wide range of research areas and engineering disciplines, and generally requires capabilities which include power sources, precise mechanical actuation, sensing, locomotion, environmental interaction, and control. These areas themselves are now developing rapidly, with advancements such as high density batteries, advanced materials, micro-electronics and sensors, computer vision, GPS and navigation tools, and advanced control algorithms. Additionally, there has been considerable research into creating a more natural human-robotic interface, which includes speech recognition and generation, gesture recognition, and artificial facial expression. Several countries, most notably Japan and South Korea, have made large R&D investments in robotics over the last couple of decades, partly with an eye toward augmenting their labor pool as their societies age.

Artificial intelligence is a related field that is increasingly utilized in robotic and other control systems, but its focus is on developing intelligent machines or systems, and it is sometimes defined as a branch of computer science. However, today it involves a wide range of research and problem areas, such as reasoning, planning, learning, perception, and environmental and situational awareness, which are studied by a broad range of disciplines, including engineering, psychology, and philosophy. The development of "weak AI," namely, the cognitive ability to solve specific problems or perform specific tasks, has been demonstrated in a broad range of applications over several decades. It is becoming increasingly important to facilitate many "smart" technologies now available commercially. However, the development of "strong AI," or true general intelligence and creativity similar to a human brain, is a long-term goal that some believe may never be realized.

Robotics, artificial intelligence, and human augmentation have become very important technologies not only because of their military and industrial applications, but also as a burgeoning economic sector and a potentially transformative social driver. In this vein, in June of 2011, the Obama Administration launched the National Robotics Initiative,[138] a partnership between the NSF, National Institutes of Health (NIH), National Aeronautics and Space Administration (NASA), and U.S Department of Agriculture (USDA), which is designed to move forward on a broad research front to develop a wide range of robots that can work alongside humans in a variety of settings.

Transformational Technologies: Specific technology and application areas which are evolving rapidly and are having major impacts include:

- *Industrial Robotics:* Robotic systems have been used in industrial settings since the early 1960s, and it is currently estimated that there are over 8.4 million such robots in use globally,[139] with a projected world market of over $15 billion by 2015.[140] Increasingly cheap and capable sensors, actuators, and control systems are dropping the cost of robotic systems

[138] See http://spectrum.ieee.org/automaton/robotics/industrial-robots/obama-announces-major-robotics-initiative
[139] See http://www.worldrobotics.org/
[140] See http://www.roboticsbusinessreview.com/article/consumer_robot_sales_to_surpass_15b_by_2015

dramatically, as well as rapidly expanding the tasks they can do and the complexity of products they can make. The standardization and modularization of robotic components is also increasing flexibility and dropping costs. These developments will likely have increasingly profound consequences for labor forces worldwide, but especially in developing countries, where robotic systems may become even cheaper than their low wage human workers. It will also mean developing countries will be able to manufacture increasingly sophisticated products themselves, perhaps changing the balance of global economic competition and even the national security environment.

- *Health and Medicine:* A rapidly expanding sector of commercial robotics is in health and medical applications, driven by the generally high value of its products and services, as well as the increasing shortage of human labor. There are already a number of commercial robotic systems available to assist or replace human surgeons, often with much-improved results,[141] and remote telemedicine systems are increasingly in use. A potentially large and lucrative market is in robotic patient, home, and elder care.[142] A large amount of research dollars are being invested in these systems globally by governments and corporations, although there are still considerable technical and social hurdles to overcome, principally because of concerns about the safety of human-to-robot interactions. This sector, however, may be a key driver for developing the technical, legal, and sociological tools to make robots commonplace in human society. This general area has significant implications for DoD, related to the costs of health care and personnel support, advanced battlefield care, and in the development of frameworks for the sociology of human-to-robot interactions in operational environments.
- *Unmanned Vehicles:* The area of unmanned vehicles (UVs) has become a large research and commercial sector, with a number of Federal agencies funding research, and a wide range of companies developing and producing them. There are also trade organizations and non-profit research consortia that coordinate a wide range of activities, [143] including the legal and legislative frameworks for operating UVs. Open sourcing and cheaply available components and systems have also encouraged a significant community of DIY UV developers. The global market for unmanned air vehicles alone was estimated at $7.1 billion in 2011,[144] and the United States currently accounts for about 77% of all the research, development, technology and engineering (RDT&E) on UVs worldwide.

  From a military standpoint, UVs are already making major contributions on and off the battlefield for the United States and other nations, including air, [145] ground, [146] and sea vehicles,[147] and their role will continue to expand. While this area is too large to cover in detail here, extensive information is available elsewhere, for example, the U.S. Unmanned Systems Integrated Roadmap.[148] Remote controlled vehicles of various kinds are increasingly mature technologies, and fully autonomous vehicles are still limited but evolving rapidly. Facilitating trends in these technologies include miniaturization, reduced power consumption,

[141] See http://www.intuitivesurgical.com/
[142] See http://www.roboticsbusinessreview.com/article/progress_report_on_eldercare_robots
[143] For example, see http://www.auvsi.org/Home/
[144] See http://www.unmanned.co.uk/unmanned-vehicles-news/global-unmanned-vehicles-market-expected-to-grow-by-4-over-the-next-decade/
[145] See http://www.iar-gwu.org/node/144
[146] See http://www.rsjpo.army.mil/
[147] See http://auvac.org/community-information/community-news/view/1473
[148] See http://www.defenseinnovationmarketplace.mil/resources/UnmannedSystemsIntegratedRoadmapFY2011.pdf

better sensors and navigation tools, advanced materials, and more substantial armaments. For autonomous vehicles, artificial intelligence and system control are still the primary limiting factors, particularly when they are to operate in concert with each other or conventional forces. DoD is funding considerable research on improved intelligent control systems, and significant advances are expected over the next five years.

Unmanned vehicles could also make significant contributions in civilian environments, for example, for surveillance, infrastructure monitoring, police telepresence, and homeland security applications. However, operational safety in urban or built environments has been a major issue so far, which extends to legal and liability concerns. One significant development recently has been the testing of unmanned commercial automobiles. Although Google has had a high profile program, almost all the major auto companies have significant autonomous domestic vehicle research programs, as does the Department of Transportation, NASA, and parts of DoD.[149] In another interesting development, Amazon recently announced plans to develop a system to deliver packages by fleets of unmanned drones[150] although there has already been some backlash from the public and regulatory bodies. These programs significantly benefit the U.S. military efforts in these areas because they add private sector resources, help resolve issues of safety and human interaction, and increasingly are evolving the legal and legislative frameworks for operating such vehicles in populated areas. In fact, there are currently three states that issue vehicle permits for driverless cars. As these capabilities accelerate, the U.S. military will be able to take advantage of such systems for a much broader array of support functions, relieving human personnel for more substantive tasks.

- *Hazardous Operations:* Synergetic with the technologies being developed for military operations are those for a variety of operations in hazardous or extreme environments. These include space exploration,[151] emergency response and firefighting,[152] bomb and hazardous waste disposal,[153] police support duty,[154] search and rescue,[155] and mining.[156] While these technologies typically parallel that of military systems, they often add additional operational capabilities, such as being designed to withstand extremes of temperature, radiation, or other unusual circumstances. These applications are important for DoD robotics efforts in general because they create additional private sector markets for niche capabilities, which will ultimately drive additional innovation and lower costs.
- *Service and Domestic Sector:* Service robots for personal use represent the fastest growing segment of the robotics industry, and it is estimated that almost 11 million units will be sold worldwide between 2012-2015, with a total value of almost $4.8 billion.[157] Dozens of

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149 See http://www.nationaldefensemagazine.org/archive/2011/August/Pages/Army,CarMakersPushAheadWithDriverlessVehicleResearch.aspx

150 See http://www.cnn.com/2013/12/02/tech/innovation/amazon-drones-questions/

151 See http://robotics.nasa.gov/

152 See http://www.allonrobots.com/firefighting-robots.html

153 See http://www.nationaldefensemagazine.org/archive/2011/July/Pages/NewRobotsPlannedforBombDisposalTeams.aspx

154 See http://www.policeone.com/police-technology/articles/6003779-Ariz-cops-to-get-robots-to-help-in-dangerous-situations/

155 See http://news.cnet.com/8301-17938_105-20042945-1.html

156 See https://share.sandia.gov/news/resources/news_releases/miner-scou/

157 See http://www.worldrobotics.org/

companies now manufacture service related robots, with capabilities that include vacuuming, lawn mowing, dog walking, indoor courier service, kitchen helper service, grooming, elder assistant service, as well as a wide range of entertainment functions.[158] These robots tend to have very limited artificial intelligence, although this is improving rapidly. Another increasing use is in public relations, for example as robotic receptionists, salesmen, or tour guides, and this involves research into creating more lifelike and fully functioning humanoid robots, such as Honda's Asimo. [159] While this market segment is driving considerable innovation in niche areas, it also must also deal with novel problems, such as human acceptance of robotic form and presence in close proximity, and the mimicking of human expression.

- *Embedded Systems:* While not strictly robotics, the accelerating trend toward embedded systems parallels robotics development and is already having a major effect on some aspects of society. Embedded systems generally refer to physical systems which incorporate digital or analog electronic devices, microprocessors, sensors, actuators, software, communication devices, and often Micro-Electro-Mechanical Systems (MEMS) or mechanical systems, and are usually focused on real-time operation.[160] Smart phones are now the canonical example of an embedded system; however, nearly every major industry is now incorporating embedded systems of various kinds in their products. At present, examples of embedded systems exist in automobiles, factories, infrastructure, appliances and homes, pets, and potentially, inside human beings. As new paradigms such as "cloud robotics" become prevalent,[161] the line between conventional robotics and intelligent everyday devices will become increasingly blurred. The profound ramifications of this trend are that nearly every aspect of global society could become instrumented, networked, and potentially available for control via the Internet, in a hierarchy of cyber-physical systems.[162] With cybersecurity still an increasingly serious global problem, embedded systems may present even more severe privacy and security issues.
- *Human Augmentation:* Advanced robotic devices that can augment human physical or cognitive abilities is an area that is also rapidly developing. Although often related to the replacement and regeneration of biological tissues, covered in Appendix B, many purely robotic devices are being developed that can temporarily enhance a human being's characteristics for special tasks. For example, exoskeletons, which could impart greatly increased physical characteristics, are in their early stages of development and have great promise.[163] Recently, researchers demonstrated a "Spidersense" suit,[164] which significantly enhances sensory perception of a wearer's environment and could be modified to detect a wide range of phenomena. Google, which developed Google Glass to provide wearable computer and network access, is developing a contact lens version.[165] Research in direct

[158] See http://www.trendhunter.com/slideshow/domestic-robots
[159] See http://world.honda.com/ASIMO/
[160] See http://eetimes.com/discussion/other/4204667/Emerging-trends-in-embedded-systems-and-applications
[161] See http://www.roboearth.org/cloud_robotics
[162] See http://cyberphysicalsystems.org/
[163] See http://techland.time.com/2012/10/15/meet-x1-the-exoskeletal-robot-suit-that-could-make-astronauts-super-strong/
[164] See http://www.gizmag.com/spidersense-suit/26592/?utm_source=Gizmag+Subscribers&utm_campaign=4475661ac6-UA-2235360-4&utm_medium=email
[165] See http://www.digitaltrends.com/mobile/google-considers-tiny-cameras-for-contact-lenses/#!GvDCw

brain-to-device interfaces is already a developing field, [166] and recently researchers demonstrated two human brains communicating directly over the Internet.[167] This range of technologies is now more generally referred to as the field of *bionics*, and has potentially profound implications for a wide range of applications, in particular, warfighter capabilities, as well as support personnel capabilities.

- *Weak AI:* As described above, "weak AI" generally refers to limited machine intelligence focused on decisionmaking for a specific problem area. Weak AI can be implemented by a variety of methods, such as rule sets, statistical methods, neural nets, and adaptive or learning algorithms. Weak AI is currently present in a wide range of technologies, from sensor systems and infrastructure control, to human interfaces, and is improving steadily due to software developments and increasing computer speed. There is a huge community of researchers developing new weak AI capabilities, including many in DoD. [168] However, improvements in cognition of weak AI systems are still qualitatively incremental.
- *Strong AI:* Strong AI has been the holy grail of artificial intelligence research for decades. Strong AI seeks to build a machine which can simulate the full range of human cognition, and potentially include such traits as consciousness, sentience, sapience, and self-awareness. No AI system has so far come close to these capabilities; however, many now believe that strong AI may be achieved sometime in the 2020s. Several technological advances are fostering this optimism; for example, computer processors will likely reach the computational power of the human brain sometime in the 2020s (the so-called "singularity"). Other fundamental advances are in development, including exotic/dynamic processor architectures, full brain simulations,[169] neuro-synaptic computers,[170] and general knowledge representation systems such as IBM Watson.[171] It is difficult to fully predict what such profound improvements in artificial cognition could imply; however, some credible thinkers have already posited a variety of potential risks[172] related to loss of control of aspects of the physical world by human beings. For example, a 2013 report commissioned by the United Nations has called for a worldwide moratorium on the development and use of autonomous robotic weapons systems until international rules can be developed for their use.[173]

National Security Implications: Over the next 10 to 20 years, robotics and AI will continue to make significant improvements across a broad range of technology applications of relevance to the U.S. military. Unmanned vehicles will continue to increase in sophistication and numbers, both on the battlefield and in supporting missions. Robotic systems can also play a wider range of roles in automating routine tasks, for example in logistics and administrative work. Telemedicine, robotic assisted surgery, and expert systems can improve military health care and lower costs. The built infrastructure, for example, can be managed more effectively with

[166] For example, see the University of Michigan project: http://www.umich.edu/~umdbi/

[167] See http://www.washington.edu/news/2013/08/27/researcher-controls-colleagues-motions-in-1st-human-brain-to-brain-interface/

[168] See http://www.militaryaerospace.com/articles/2013/03/DARPA-machine-learning.html

[169] See http://www.kurzweilai.net/waterloo-researchers-create-worlds-largest-functioning-model-of-the-brain?utm_source=KurzweilAI+Weekly+Newsletter&utm_campaign=d92f0f2be5-UA-946742-1&utm_medium=email

[170] See http://www.gizmag.com/ibm-neurosynaptic-computer-chips/19562/

[171] See http://www.computerworld.com/s/article/9237343/IBM_Watson_will_eventually_fit_on_a_smartphone_diagnos

[172] See http://www.fastcoexist.com/1678899/how-stephen-wolfram-is-preparing-for-the-singularity

[173] See http://phys.org/news/2013-05-moratorium-killer-robots.html

embedded systems, saving energy and other resources. Increasingly sophisticated weak AI tools can offload much of the routine cognitive or decisionmaking tasks that currently require human operators. Assuming current systems move closer to strong AI capabilities, they could also play a larger and more significant role in problem solving, perhaps even for strategy development or operational planning. In the longer term, fully robotic soldiers may be developed and deployed, particularly by wealthier countries, although the political and social ramifications of such systems will likely be significant. One negative aspect of these trends, however, lies in the risks that are possible due to unforeseen vulnerabilities that may arise from the large scale deployment of smart automated systems, for which there is little practical experience. An emerging risk is the ability of small scale or terrorist groups to design and build functionally capable unmanned systems which could perform a variety of hostile missions.

Appendix D: Revolution in ICT and Cognitive Science

General Trends: The ICT that have been developed and widely deployed over the last three decades have driven some of the greatest change in human history. Not only are ICT globally connecting mankind, but ubiquitous flows of information are facilitating profound changes in the industrial, transportation, energy, media, defense sectors, and others, as well as changing the way governments operate. The networking of people and things continues to expand from the largest scales (global networks) to the smallest (embedded microsensors). As such, data and information is being produced at a hyper-exponential rate.[174] Technologies which digitally store and process data and information, such as microprocessors and memory, continue to improve rapidly, but at a slower rate than information production. Tools to help human beings process and understand this information deluge are developing at an even slower rate, and this cognitive mismatch is already presenting significant dilemmas for operations, governance, and organizational and personal decisionmaking.

ICT generally facilitate information pull, information push, information analysis, and increasingly, information effects. Technologies facilitating information pull include physical devices like PCs and smart phones, environments like browsers, and search and query tools like Google. Technologies to push information to potentially large numbers of other users include the above, as well as social networking sites, blogs, tweets, and other emerging digital media. ICT also provide a range of analysis tools, such as expert systems, modeling and simulation, visualization tools, and the like. And increasingly, ICT can be used to affect the physical world, for example through Internet-based industrial controls (IC) and SCADA (Supervisory Control and Data Acquisition) systems, embedded systems, web-based logistics, and the ICT themselves (e.g., via hacking). All of these capabilities have benefits and risks which are poorly understood, since their evolution is extremely rapid and there is little historical precedent for such large scale developments.

These developments have an increasingly wide range of consequences for the U.S. national security community, the Federal Government, and in fact organizations worldwide. Ubiquitous online information and ICT will transform environmental sensing, situational awareness, intelligence gathering, logistics and resources, command and control, marketing and business, public relations and diplomacy, and education and training, and improve human cognition and creativity. However, new concepts and tools will be needed to keep pace with this evolving global landscape and harness its potential. Some of the transformational technologies which could provide, or are affecting, these capabilities are discussed below.

Transformational Technologies: Specific technology and application areas which are evolving rapidly and are having major impacts include:

- *Ubiquitous Sensing:* The deployment of electronic sensors to collect data has exploded in recent years, and includes traditional sensors from environmental monitoring, infrastructure systems, transportation, medicine, and the like, and increasingly, mobile electronic devices, which contain a variety of data gathering elements. Moreover, a rapidly increasing amount of data is generated or gathered by ICT themselves, such as data about Internet operations or

[174] Marcia Connor's blog, in a post on "Data on Big Data" recently stated that: "Every day, we create 2.5 quintillion bytes of data—so much that 90% of the data in the world today has been created in the last two years alone." http://marciaconner.com/blog/data-on-big-data/

traffic, video feeds, and metadata (i.e., data about data). In 2010 it was estimated that there may be up to 1 trillion sensors now connected to the Internet,[175] a number which may quadruple by 2020. Many kinds of new ICT-based sensor technologies are also in development, such as wearable biosensors[176] and networks of nanosensors,[177] and as wireless deployment expands, these will all increasingly contribute to the flood of online information. While this represents enormous opportunity for understanding and managing the global environment, the potential for illicit or malicious activities also is increasing greatly, as these resources become widely available to nearly everyone.

- *Big Data:* Big data is a relatively recent term that refers to the extremely large digital databases of stored or transmitted information collected from a range of sensing systems, as well as data from Internet traffic, cell phones, video recordings, social media, and other sources. As noted earlier, all such data sources together produce about 2.5 quintillion bytes of data[178] per day, about 80% of which is unstructured, and the rate of increase only seems to be accelerating. There is currently much enthusiasm about big data as a potential tool for understanding, analyzing, and managing many aspects of society, such as transportation, energy use, natural resource prospecting, public health, security and law enforcement, as well as new concepts such as smart cities and crowdsourcing. However, as these databases continue to grow, there are increasing challenges in the ability to mine and analyze them. New tools such as MapReduce, Hadoop, and behavioral biometrics are improving these capabilities, however there will continue to be challenges in dealing with the volume, velocity, variety, and veracity[179] of such large data sets to help make better decisions.
- *New Computing Architectures:* At the core of ICT lie computer processors and memory, which perform digital computation and storage functions. For several decades, computer power has doubled roughly every two years ("Moore's Law"), and this has driven the extremely rapid advances of the information revolution. However, current silicon-based computer architectures are reaching their physical limits. A number of new technologies are being developed to continue the increases in computer power, some of which may be revolutionary. In the near term, advancements such as improved lithography, heat dissipating materials and true 3D chip architectures[180] will likely extend silicon chip density increases into the 2020s. Optical computers are another near term possibility, and offer advantages in speed and power consumption. Most of the necessary components for optical computing have already been developed,[181] although a commercial optical computer may not be fielded until the 2020s. Biocomputers, which typically perform operations using complex molecules such as DNA, could perform huge numbers of parallel calculations at once, and have been in development for decades. However, there are still significant technological hurdles which may keep them from commercial deployment until at least the late 2020s. Finally, quantum computers are the most exotic and potentially transformational new computing technology, since they actually exploit the quantum nature of matter. Quantum computers would not be

[175] See http://websimpletools.com/2010/09/mother-earth-gets-a-central-nervous-system-1-trillion-sensors/

[176] See http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=4650309&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D4650309

[177] See http://www.ece.gatech.edu/research/labs/bwn/surveys/wnsn10.pdf

[178] See http://marciaconner.com/blog/data-on-big-data/ , *op. cit.*

[179] See http://www-01.ibm.com/software/data/bigdata/

[180] See http://phys.org/news187454589.html

[181] See http://phys.org/news/2012-03-holey-optochip-trillion-bits-power.html

limited to conventional binary logic, could exploit other exotic properties such as a quantum entanglement, and would have near infinite speeds in comparison to current silicon computers.[182] Many organizations are funding research on quantum computing, including DoD, and remarkable progress has been made in recent years, but several profound technical barriers remain. Still, some researchers have predicted that special purpose quantum computing architectures may be available within one to two decades.[183]

- *Ubiquitous Networks:* Along with ubiquitous sensing and big data, ubiquitous availability of Internet connectivity promises to be another transformational trend. Deployment of devices to access the Internet continues to rapidly expand, with nearly 7 billion devices and about 4 billion human users currently connected, and 6 billion users likely by 2020. Internet penetration is growing by 40% per year globally, a majority of which is occurring in undeveloped countries, and many countries are now deploying 1 Gb Internet backbones. Network speeds and WiFi availability have now become key indicators for macroeconomic analysts. As cloud and grid computing also become increasingly available, it is possible that within a decade almost every human being, globally, will have access to enormous data resources and sophisticated analytic tools. With the evolution of the IoT,[184] they will also have information about, and potentially limited control over, a wide range of physical devices and systems. Further, wearable access technologies, such as Google Glass and potentially direct human-computer brain interfaces, may mean that human beings will have the ability to be "always online" within a decade.[185]
- *Social Media:* Social media environments represent one of the most important web based technologies yet developed, and they continue to expand rapidly in sophistication, user base, and commercial influence. Current estimates are that 2/3 of the U.S. population uses social media regularly,[186] and the user growth rates in developing countries are particularly high, for example, by as much as 50% yearly in India and Indonesia.[187] This penetration is likely to continue as their mobile versions, or SoMo, proliferate, and there is increasing integration across environments and technology platforms. Social media, such as LinkedIn, Facebook, and Twitter, allow users to search for, connect to, and exchange information and opinions with large numbers of other users globally. They incorporate many conventional information sources, and increasingly they are facilitating the emergence of new social phenomena such as "digital tribes."[188] Such emergent phenomena have already produced important effects, such as enhancing political campaigns, and helping organize political demonstrations and even insurgencies such as the Arab Spring.[189] Many governments are now trying to utilize these technologies for more transparent governance, but also increasingly for soft power, public relations, and diplomacy on a global scale, which is now being termed "cyber statecraft." The business and economic applications of social media have been developing for some time, for example for marketing analysis, but an important new trend is in

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182 See http://www.slate.com/blogs/future_tense/2013/03/20/quantum_computing_and_the_future_of_moore_s_law.html
183 See http://www.bbc.co.uk/news/science-environment-17688257
184 See http://qz.com/156075/internet-of-things-will-replace-the-web/
185 See http://www.marketplace.org/topics/tech/always-internet-2013-and-controlling-robotic-arm-brain-implant
186 See http://www.pewinternet.org
187 See http://searchenginewatch.com/article/2242467/Global-Social-Media-Trends-in-2013
188 See *Emerging Data Models to Help Serve Tomorrow's Digital Tribes*, KPMG International 2009.
189 See http://www.washington.edu/news/2011/09/12/new-study-quantifies-use-of-social-media-in-arab-spring/

crowdsourcing, crowdfunding, and open design, which could greatly increase innovation in many sectors.

- *Virtual Reality/MMOG/Telepresence:* Somewhat related to social media are environments for virtual reality (VR). These generally comprise 3D digital environments of high detail, in which human subscribers can generate and manipulate a virtual avatar to interact with other players and virtual objects. Diverse organizations have already developed some kind of VR presence, including many Federal agencies[190] and many cities and states. SecondLife, started in 2003, was the first sophisticated VR environment and also developed much of the early innovation. At its peak it had several million subscribers exchanging millions of real dollars through its virtual economy. Today, however, the largest environments are Massively Multiplayer Online Games (MMOG), which are competition oriented environments, of which there are now hundreds. These games are significant because of the sheer size of their enterprise: World of Warcraft has over 12 million subscribers worldwide, while Happy Farm has over 228 million registered subscribers. The financial aspects of MMOG are staggering; U.S. MMOG gamers spent over $3.8 billion in 2010, and the value of virtual property in some games ranks their economies above many nations. These environments, however, may have considerable national security implications; they are known to be collaborative environments for terrorists and criminal organizations [191] and environments for money laundering. Conversely, they are also excellent environments for open source intelligence gathering.

  Much has been written about VR environments for training and educational aspects, and many institutions such as universities and museums have generated 3D renderings of their facilities. The U.S. military has funded the development of these environments for years as training devices, and currently has projects for PTSD treatment,[192] squad tactics,[193] a variety of flight simulators, cultural training, medical training, and potentially, a persistent, individualized personal avatar[194] for each soldier. Technologically, great strides are now being made in 3D virtual visualization systems, whole body instrumentation, and virtual behavioral mapping, which could provide a natural, effortless, and seamless interface to a VR environment. A related application is to telepresence, in which a person's physical form, voice, and behavior are represented remotely via digital media, for example, a full 3D hologram, or even a robotic form. Telepresence[195] has potential for enhanced remote meeting and negotiations capabilities, or even for enhanced remote operations, for example, hazardous operations or space travel. Whether these capabilities may also enhance terrorism or criminal operations, remains to be seen.

- *Cybersecurity:* Although cybersecurity has been an increasingly important priority for the United States and other nations for a decade, in many ways the global situation has worsened in recent years. Because it is currently a high profile topic, with much written and said about it, we will not focus on it here. However, two recent trends which may have grave security implications should be noted. The first is the increasingly large and transparent offensive

[190] See http://www.fcvw.org/
[191] See http://singularityhub.com/2011/08/24/al-qaeda-in-azeroth-terrorism-recruiting-and-training-in-virtual-worlds/
[192] See http://minnesota.publicradio.org/display/web/2012/11/29/daily-circuit-virtual-reality-ptsd
[193] See http://www.army.mil/article/84453/
[194] See http://www.wired.com/dangerroom/2012/01/army-virtual-reality/
[195] See http://www.telepresenceoptions.com/2011/06/telepresence_and_visual_collab_2/

operations in cyberspace by certain nations, which suggest an increasing militarization of cyberspace, and perhaps even a cyber arms race. A recent report by the DSB has concluded that the U.S. military is unprepared for a cyber offensive by a top-tier adversary, and has recommended increasing offensive cyber capabilities.[196] The second point is the increasing vulnerability of mobile devices to malicious cyber activities as their hardware and software becomes more sophisticated. As mobile devices, including embedded systems, proliferate faster across the globe, the effects of major cyber attacks via these "attack surfaces" may become increasingly severe and difficult to anticipate.

- *Cognitive Enhancement and Collective Intelligence:* ICT will continue to increase the global flow of data, information, and knowledge dramatically, at least for the foreseeable future. Ultimately, however, individuals need to understand this sea of information to make use of it, a task which is only likely to get harder. Tools to enhance human cognition will therefore become increasingly important. Cognitive enhancements could generally take the form of devices, actual physical augmentation of the brain, or a hybrid of both.

  Examples of cognition enhancing devices include mobile devices which use situational and contextual information to prioritize and predict the most relevant information for the user, which has already been demonstrated for traffic navigation applications. Other applications include biologically inspired search algorithms for big data, which mimic some of the cognitive aspects of the human brain (e.g., IBM's Watson). Interactive, geometric, multidimensional data representation environments, such as Oblong,[197] are already seeing important applications. More long-term developments could include distributed human-machine systems employing brain-machine interfaces and analog physiomimetic processors, [198] as well as hybrid cybernetic systems, which could provide seamless and artificially enhanced human data exploration and analysis.

  A number of technologies for directly enhancing human cognitive capabilities were mentioned earlier in the biology section, and many of these are directly applicable to improved information processing. These technologies are still early in their stages and results are uneven. However, developments in the enhancement of human cognition on a macro-scale are becoming more mature. Studying the emergence of collective intelligence[199] from large human-machine systems is an important new discipline, building on aspects of complex adaptive systems. Other more mature efforts, such as The Millennium Project,[200] utilize existing ICT to mine the knowledge and creativity of worldwide networks of experts to help develop solutions to complex problems. The longer term evolution of these trends may be the emergence of the "global brain," a concept proposed in the late 1990s, in which all human beings are constantly connected through ICT into one macro-intelligence. Several notable institutes are already studying the possibility of this phenomenon and the capabilities it could provide.[201]

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[196] See http://www.homelandsecuritynewswire.com/dr20130306-u-s-military-unprepared-for-cyberattacks-by-toptier-cybercapable-adversary-pentagon

[197] See http://gigaom.com/2013/02/18/video-grabbing-data-and-pushing-pixels-a-visit-with-oblong-industries/

[198] See http://www.synesisjournal.com/vol2_no2_t1/GiordanoWurzman_2011_2_1.pdf

[199] See http://cci.mit.edu/

[200] See http://www.millennium-project.org/

[201] See http://globalbraininstitute.org/

National Security Implications: As with society as a whole, ICT will facilitate a very wide range of future capabilities for DoD. Perhaps the greatest challenge will be in keeping pace with the rapid evolution of ICT, and in developing appropriate doctrine, operational structures, and decisionmaking to exploit them. The Chinese, for example, are already studying the military uses of the global IoT, [202] and are building capabilities to exploit it. [203] However, DoD has had significant issues in the past acquiring and deploying cutting edge ICT from the private sector, and using them effectively. Another major challenge in the future will be in dealing with the asymmetries arising from ubiquitous ICT, as small groups or even individuals are able to create temporary but significant operational advantages for malicious ends, using cyber resources which are essentially free.

The most direct military application of advanced ICT will lie in the areas of Command-Control-Communications, Computers and Intelligence-Surveillance-Reconnaissance (C4ISR). Over the next 20 years, the most consequential advancements for C4ISR will be the availability of enormous amounts of information, collected from entities almost everywhere, in real time, through pervasive network access. Commercial ICT will be an important part of this capability. The challenge for DoD will be how to use these developments to out-think our adversaries. World-class organizations such as the National Security Agency (NSA) can provide exceptional insights, but decisionmakers must know how to use them. C4ISR will also have to meet the still undefined demands of future cyber war. Since cyber can disrupt nearly all elements of remote observation (the "observe" part of the Observe, Orient, Decide, Act (OODA) loop), it can dominate the entire decision cycle. Moreover, with the near-zero cost of entry into information space, and the explosion of open source information, adversaries will be able to deceive, deny and disrupt our data, while building their own awareness. Big data, and its successors, may offer many invaluable insights, but the fog of war will remain so long as there are adaptive enemies.

[202] See http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6273031
[203] See http://fmso.leavenworth.army.mil/OEWatch/201309/China_04.html

Appendix E: The Revolution in Nanotechnology and Advanced Materials

General Trends: Advances in materials have been key to human progress for millennia. Today, the revolution in new materials and nanotechnology have become comparable to the revolutions in biology and ICT. Advanced materials, such as composites and multifunctional materials, are adding improved performance and lowered weight and cost to a wide range of products. While generally incremental in their technological advancement, such novel composites and functional materials are now being widely produced and deployed, and will cause widespread changes in many commercial sectors and built environments.

Nanotechnology, generally a shorthand for "nanoscience, nanoengineering, and nanotechnology," is a collection of concepts, methods, and tools that have been developing for several decades, and it sometimes also refers the products that come from them.[204] The aim of nanotechnology is to be able to measure and manipulate matter on the atomic scale, and the goal is eventually to be able to routinely design and create materials and devices at that scale. Within the last decade, many of these tools and methods have matured, and when they become widely commercialized, many believe it will result in the "next industrial revolution."

Nanotechnology spans nearly all research and engineering disciplines, and product development is increasing in every business area. The U.S. Government coordinates nanotechnology development across 26 Federal agencies via the National Nanotechnology Initiative (NNI), funded at about $2 billion in 2013. However, many other nations have developed their own national nanotechnology programs, aimed at capturing a share of the global market for nano-related products, which some estimate to be as large as $3 trillion by 2020. This global competition is becoming increasingly sharp, with almost $10 billion spent this year on research worldwide by governments and the private sector,[205] and with roughly 2,100 nanotech companies from 48 countries in existence as of late 2010.[206] A handful of nations are now investing large amounts for commercialization, and are aggressively acquiring intellectual property and small businesses, often from the United States. Rusnano,[207] a commercial investment fund that is buying many U.S. nanotech companies and was capitalized at $10 billion in 2012, has Russian President Vladimir Putin's personal backing. Recently China opened SuZhou,[208] a city devoted entirely to nanotechnology research and commercialization, which is targeted to employ 200,000 workers.

Generally, the methods and facilities for manufacturing these materials involve a very advanced set of technologies, and are often very capital intensive. There is a global race now to develop the science, industrial processes and production capabilities for these advanced products, with trillions of dollars in market share at stake. Who wins and loses this race will have serious implications for future geopolitics and national security.

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[204] See http://www.nano.gov

[205] See http://www.electronics.ca/presscenter/articles/1542/1/Annual-Global-Nanotechnology-Research-Funding-Running-at-10-Billion-Per-Year/Page1.html

[206] See http://www.prweb.com/releases/nanotechnology/companies/prweb4203334.htm

[207] See http://en.rusnano.com/about

[208] See http://www.nanotech-now.com/columns/?article=469

Transformational Technologies: Specific technologies and application areas in advanced materials and nanotechnology which are evolving rapidly and are having major impacts include:

- *Composites and Hybrid Materials:* Composites and hybrid materials are typically combinations of existing materials into new ones with enhanced properties. Modern material science has become extremely innovative in developing tools and methodologies to design and create composites such as modeling, joining, blending, and embedding in matrices. New classes of materials include new ceramics, hybrid metals, and new polymers, as well as combinations of these. These materials can have highly enhanced properties, such as being much stronger, lighter, or more wear resistant than conventional materials, or having novel electrical, optical, or even biomimetic properties. These materials are having significant effects on many industries, including construction, transportation, energy production, textiles, health care, and defense. For example, the new Boeing 787 is achieving some 20% greater fuel efficiency than earlier competing aircraft through the extensive use of carbon reinforced plastic composites. DoD has funded materials science for decades, and has a wide range of programs to develop advanced materials for armor, superstructures, paint and coatings,[209] and having exotic electrical or optical properties, or other functional properties such as self-healing, or energy or moisture harvesting.[210] Such materials will continue to enable new defense capabilities across a range of applications. However, a future challenge will be to maintain the leading manufacturing base for these products here in the United States, as research and production become globalized. With the global market size for composite materials estimated at $57 billion by 2014,[211] there is widespread competition.
- *Smart Materials:* Smart materials are materials that can respond to their environment or external stimuli in a specific, controllable fashion. There are a wide range of such materials already in development or available commercially. The materials themselves can include polymers, ceramics, plastics, metals, carbon fibers, glasses, and others which are engineered to respond to many kinds of stimuli, such as light, heat, stress, humidity, electric or magnetic fields, and pH. Applications include structural materials that can change shape or color on demand, self-cleaning materials, pharmaceuticals that are released only when specific conditions appear in the patient,[212] materials that heat or cool with optical or electromagnetic stimuli, and clothing which can alter shape, color, or moisture exchange according to the wearer's conditions.[213] The next generation of smart materials will include embedded sensors and communication devices, distributed actuators, energy harvesting, shape control for aerodynamics and hydrodynamics, exotic optical properties, and self-healing properties. Commercially, the global market for smart materials is expected to jump from $19 billion in 2010 to over $40 billion by 2016.[214] Smart materials can have many important applications for DoD,[215] for example wearable or printable electronics to monitor soldiers physiological state, self-healing coatings and paint for ships,[216] self-healing body armor, piezoelectric thin

[209] See http://www.jhuapl.edu/newscenter/stories/st100615.asp
[210] See http://www.darpa.mil/Our_Work/DSO/Focus_Areas/Materials.aspx
[211] See http://nanopatentsandinnovations.blogspot.com/2009/12/21-billion-global-composite-materials.html
[212] See http://www.jhuapl.edu/newscenter/stories/st100615.asp
[213] See http://www.attendly.com/if-you-want-to-build-the-future-you-need-to-understand-smart-materials/
[214] See http://downloads.hindawi.com/journals/smr/si/ctsma.pdf
[215] See http://www.slideshare.net/Anupam_Tiwari/smart-materials-for-military-applications
[216] See http://www.jhuapl.edu/newscenter/stories/st100615.asp

films for acoustic sensing, hydrodynamic shape control for aircraft and micro-air vehicles, a variety of advanced medical applications, and smart dusts.[217]

- *Nanomaterials:* Nanomaterials are materials that are structured at the nanoscale, between 1 and 100 nanometers, roughly the scale of a one to a few atoms. Materials structured at the nanoscale can have exotic properties not exhibited by the same material without such structure. Nanomaterials were the first wave of nano-related products to be commercialized, and over 1,000 products are now being sold. Currently, the majority of these materials are sold as additives for a wide variety of other products, for example nanosilver in sunscreens, nanogold for medical treatments, and carbon nanotubes in sports equipment. These additives can significantly enhance the performance properties of such products, and often at relatively low cost. However, many nanomaterials exhibit other unusual properties which are more important. For example, carbon nanotubes can be excellent conductors of electricity, and are already being developed as a lighter, more robust substitute for standard copper wiring and potentially electronics. More exotic are meta-materials, which are conventional materials with precise patterns engraved on them at the nanoscale, for example extremely thin films which form nano-antennae. Nanomaterials could have an extremely wide range of applications for the military, and are currently being developed for novel body armor,[218] very strong but light structural elements,[219] and carbon nanotube cables and sheeting,[220] among others. Graphene, essentially the first two dimensional material, could revolutionize electronics,[221] among other areas. Long-term potential uses include stealth coatings, self-healing materials, adaptive camouflage, electromagnetic shielding,[222] and smart skins.[223] These materials will undoubtedly provide significantly new capabilities over the next decade; however, it is not clear whether the United States will be able to maintain its lead in global development and production.
- *Nanoelectronics:* In keeping with Moore's law, current semi-conductor devices have decreased in size to the point where their smallest length scales are already within the nanoscale (i.e., 22 nanometer lithography). However, current silicon architectures generally do not exploit the exotic properties that are possible at the nanoscale, where for example quantum mechanical effects can dominate. Development of nanoelectronic devices will not only extend Moore's law, but provide truly new and transformational capabilities. Many governments and companies worldwide are investing large R&D amounts in this area. Nanoelectronics is probably the area of nanotechnology that is most ripe for commercialization, with the global market for nanoelectronics expected to reach over $400 billion by 2015.[224] A significant U.S. innovator is the Nanoelectronics Research Initiative,[225] a part of SemaTech, which funds university research through a consortium of industry and Federal funding. Recently, the state of New York, IBM, and the University of Albany partnered to create the world's largest research and commercialization center for nanoelectronics, reportedly capitalized at over $7 billion.

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[217] See http://robotics.eecs.berkeley.edu/~pister/SmartDust/
[218] See http://www.businessinsider.com/mit-body-armor-breakthrough-2012-11
[219] See http://www.gizmag.com/zyvex-piranha-usv/22078/
[220] See http://www.nanocomptech.com/
[221] See http://www.technologyreview.com/news/421853/making-graphene-nanomachines-practical/
[222] See http://www.nanowerk.com/spotlight/spotid=27088.php
[223] See http://www.nanowerk.com/news2/robotics/newsid=27943.php
[224] See http://www.prweb.com/releases/nanoelectronics/nanotechnology/prweb2493854.htm
[225] See http://www.src.org/program/nri/

Nanoelectronics research is developing a range of new tools and devices which exploit fundamental atomic and quantum mechanical properties of matter. These include nearly one-dimensional lithographic methods, nanowires, quantum dots, molecular computing, spintronics, and nanophotonics. These technologies could allow computation and memory storage to occur using devices far smaller than current silicon technologies, and requiring far less power. Many of these new technologies have already been demonstrated in the laboratory, for example single molecule computing devices have been built by a number of research groups.[226] However, widespread commercialization of more exotic nanoelectronic devices is at least 5-10 years away. A major hurdle will be developing reliable manufacturing methodologies which can be scaled up to significant production. DARPA has recently announced the creation of the STARnet program to accelerate research in nanoelectronics,[227] funded at a minimum of $40 million per year. STARnet and other DoD programs may create the cutting edge of innovation in this field, but with the bulk of electronics manufacturing now lying outside the United States (particularly in China) it is unclear whether the United States can maintain leadership in commercialization.

- *Nanosensors:* Sensors are one of the more immediate and useful applications of nanotechnology. Nanosensors can be sensors that detect extremely small amounts (potentially single molecules) of a substance, or sensors actually constructed at or near the nanoscale. A number of commercialized technologies exist in the first category, which often exploit the extreme sensitivity of existing biological organisms or biomimetic instruments (e.g., electronic noses[228]). However, the second category, namely, sensor devices constructed at the nanoscale, will be particularly innovative. These sensors utilize nanostructures such as functionalized metallic nanoparticles, functionalized nanowires and nanotubes, macroscopic materials with nanoscale features or surface treatments, and nanostructured mechanical systems, whose properties respond to the presence of extremely small amounts of particular substances. While initially limited to a small set of substances, a number of these technologies are now appearing which can detect a fairly wide range of materials.[229] A great deal of research on nanosensors has gone on in the biological and medical world, for example, with the goal of studying individual cells or detecting molecules of pathogens or toxins with high specificity.[230] These technologies are applicable to a wide range of industries, such as the chemical industry, electronics, food safety, public health, aerospace, and homeland security. Nanosensors can be particularly important for DoD, as they may replace many conventional sensors, providing greatly increased sensitivity, lower power and weight, and potentially lower cost. More ambitious capabilities being researched include large networks of nanosensors that have wireless communication and potentially onboard processing, which could provide nearly noninvasive monitoring of a wide area to collect data pervasively.[231] Military applications include health and environment, battlefield instrumentation, and intelligence gathering, among others.

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[226] See http://www.popsci.com/science/article/2010-05/single-molecule-computes-thousands-times-faster-your-pc
[227] See http://www.darpa.mil/Our_Work/MTO/Programs/STARnet.aspx
[228] See http://www.nanowerk.com/spotlight/spotid=17373.php
[229] See http://www.popsci.com/technology/article/2011-03/new-ultra-sensitive-sensor-could-sense-any-substance-taking-light-sensing-tech-out-lab
[230] See http://www.nanoscience.ucf.edu/research/biomedical_perez5.php
[231] See http://www.ece.gatech.edu/research/labs/bwn/granet/projectdescription.html

- *Biomedical Nanotechnology and Nanomedicine:* Because nanostructures are of roughly the same scale as many biological structures, there are a wide range of applications in biotechnology and medicine. Many new nanomaterials are being developed or tested for a variety of biomedical applications, such as nanogold for cancer treatments. Nanoelectronics are being used to help develop nanobiosensors, and to provide direct interfaces to neurons. Nanosensors are also being developed to image and measure a wide range of cellular functions, both outside and inside cells. Novel drug delivery mechanisms are probably the most active area being commercialized, particularly by the pharmaceutical industry, where they can provide better skin penetration, timed or conditional drug release, nonviral gene therapy vectors, or even delivery directly inside cells. Targeted drug delivery, potentially to specific organs or body areas, is another goal, and the development of drugs designed for an individual based on their genome, for example, "personalized medicine," is an increasing area of research investment. Nanomaterials are also being investigated as frameworks for tissue reconstruction or engineering, where cells can be grown around a nanomaterial scaffolding. Longer term capabilities may include nanomachines that can operate at the cellular level, or even grow or reconstruct whole organs.

  Nanobiotechnology is a very rapidly growing commercial sector, with a global market predicted at over $6 billion by 2017.[232] A number of countries are investing heavily in it, and the NIH budget alone for nanotechnology related research in 2013 was over $400 million, with several other agencies funding their own programs. DoD can benefit widely from emerging nanobio and nanomedicine capabilities in the areas of health care and battlefield treatment,[233] as well as in the chemical/biological warfare area. The U.S. Army maintains a center devoted to nanomaterials and biology applications,[234] and the U.S. Air Force recently announced a Nano-Bio Manufacturing Consortium[235] to create a public-private partnership to develop advanced manufacturing of these products in areas such as vaccines, therapeutics, and detection technologies.

- *Nanomachines and Nanomanufacturing:* Perhaps the most ambitious goal of nanotechnology is to be able to create nanoscale devices, or nanomachines. Such devices would generally be composed of a small number of atoms that perform useful tasks on other nanoscale structures. One class, synthetic nanomachines or molecular machines, are generally designed to mimic some macroscale machine-like operation, and so far nanotechnologists have constructed molecular propellers, molecular switches, molecular tweezers, and even molecular motors. Another class of nanomachines is biologically motivated, which, for example, mimic biological structures within cells that perform physical operations, such as flagella. Significant progress has been made in this latter area; for example, scientists recently created artificial proteins, or bionic proteins,[236] potentially paving the way for entirely artificial life. Nanorobots, or nanobots, are more complex nanomachines which could potentially carry instructions to perform more complicated tasks at the nanoscale, and could include sensors

[232] See http://www.prweb.com/releases/nanobiotechnology/nanomaterials_nanotools/prweb9340108.htm
[233] See http://www.popsci.com/science/article/2012-01/mits-nano-treated-bio-bandage-can-stop-bleeding-almost-immediately
[234] See http://www.tatrc.org/ports_nanoMedBio.html
[235] See http://globalbiodefense.com/2012/11/16/nano-bio-manufacturing-consortium/
[236] See http://phys.org/news/2013-02-nano-machines-bionic-proteins.html

and communication capabilities; however, as rendered in Figure 2, these are largely notional at this time.

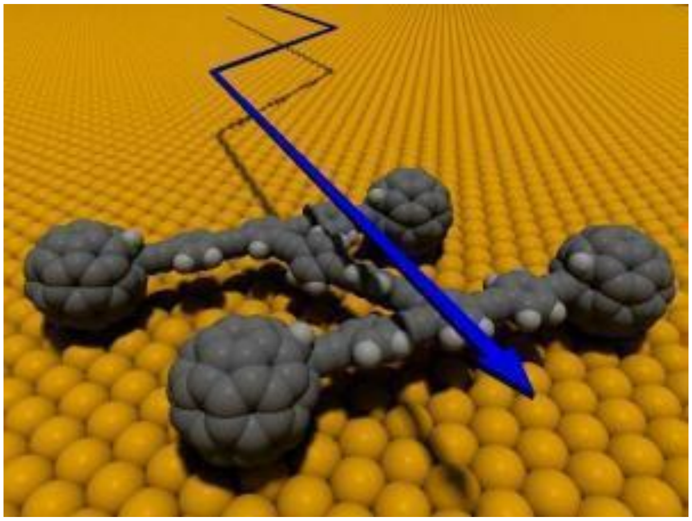

Figure 2: Molecular Car

The figure shows a computer graphic rendition of an actual molecular car with four carbon-based wheels that rolls on axles made from linked carbon atoms. See http://www.sciencedaily.com/releases/2009/04/090427080545.htm.

Nanomachines are still in their early development, and unlikely to have a major impact over the next 5 to 10 years. However, a few examples of nanomachines which act at the macro level have been demonstrated, for example large assemblies of nanomachines that can form artificial muscles.[237] Yet even if successful prototypes of nanomachines are demonstrated, many technical hurdles remain, such as reliability and robustness, and the capability to manufacture them safely and at scale. Several Federal agencies currently fund programs on nanomanufacturing, a number of companies manufacture products truly at the nanoscale, and a few promising prototype nanomanufacturing technologies have been demonstrated, [238] yet widespread development of industrial scale nanomanufacturing technologies will take a decade or more.

National Security Implications: Nanotechnologies have the potential to revolutionize almost every technology and industrial sector globally; however, in most areas they are still in laboratory development or very early commercialization. There are still significant hurdles for incorporating them in existing systems or operational environments, and there are also health and environmental concerns. DoD can and should stay on the cutting edge of research and development in these areas, both to exploit transformational technologies as they evolve, but also to mitigate risk of foreign development. One important challenge facing DoD and the United States in general is the fierce international competition for nanotechnology related intellectual property or IP, and the fact that many U.S. startups are being aggressively acquired by foreign companies. This orchestrated effort by a number of foreign countries is increasingly a threat to the nanotechnology tech base in the United States.

[237] See http://www.sciencedaily.com/releases/2012/10/121023100940.htm

[238] See http://www.webpronews.com/3d-printed-nanomachines-may-soon-be-a-reality-2012-10

Appendix F: Revolution in Energy

General Trends: The availability of energy and the technologies to deliver it have been key drivers of human advancement throughout much of history. The development of fossil fuels helped spark the industrial revolution and subsequent rapid economic growth throughout the 20th century, and still underpins the global economy. Oil in particular has created enormous wealth for some nations, and diminished the influence of others. It has also been a key driver of geopolitics and conflict since before WWII. Because the United States has become a major oil importer over the last few decades, its strategic position has sometimes been weakened. Energy security has thus become an important national goal for the United States, which will require becoming largely energy independent, and this will certainly require significant demand reduction efforts and development of new domestic sources of energy to replace imported oil. Consumption of fuel types, globally, is shown in Figure 3.

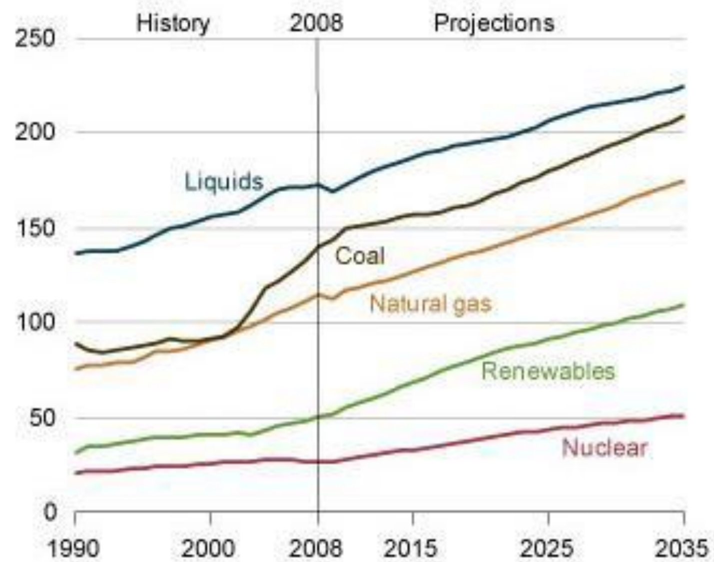

Figure 3: World Energy Consumption By Fuel, 1990–2035 By Quadrillion Btu

Figure Credits: Projected Global Energy Use, by source type, compiled by the U.S. Energy Information Administration. See: http://www.eia.gov/forecasts/ieo/world.cfm

Energy availability underlies almost all activities, large and small, that occur in daily life. Development of new technologies to produce, store, transmit, and conserve energy is a major research area globally.

The first step in energy efficiency is to reduce up-front demand, whether through design, technology or process improvement.[239] A range of significant new technologies are now on the cusp of being deployed, and other transformational technologies are in the research stage. Many

[239] The Report of the Defense Science Board Task Force on DoD Energy Strategy, "More Fight – Less Fuel," is an important study that focused on "Unnecessarily high and growing battlespace fuel demand" and the unacceptable risk stemming from the "almost complete dependence of military installations on a fragile and vulnerable commercial power grid and other critical national infrastructure…." It also called on the Department to reengineer its business processes to make energy a key factor in DoD decisions. http://www.acq.osd.mil/dsb/reports/ADA477619.pdf. See also *Reinventing Fire, op.cit.*

of these technologies are facilitated by the other technology areas of the BRINE framework. The U.S. military, as the world's largest consumer of energy, should have a major interest in these technologies, particularly in times of constrained budgets. It also has unique needs on the battlefield, particularly for vehicles and individual soldiers, and in delivering fuels to the battlefield.

Transformational Technologies: The discussion below focuses on some of the more significant and potentially transformational energy technologies now in development, with a focus on those where DoD policy decisions can make a difference.

- *Oil and Gas Recovery Technologies:* While not transformational technologies per se, the recent scale up and integration of horizontal drilling technologies and hydraulic fracturing ("fracking") methods have created a potentially transformative path for the energy future of the United States. These technologies are unlocking vast reserves of oil and natural gas in shale deposits in North America. By some estimates, the we have now roughly tripled our accessible natural gas supply, and production has been increasing at roughly 50% per year since 2007, with smaller but similar increases for oil. On this trajectory, the United States will become the world's largest natural gas producer by 2015, the world's largest oil producer by 2017, and a net exporter of energy as early as 2020.[240] The consequences of this are profound, including more robust economic growth for the United States, significantly lowered energy costs, and major shifts in geopolitical power globally, as we become less dependent on foreign resources and as major energy exporters lose income and influence.[241] While it is still too early to predict the consequences of these events, DoD would be well advised to begin assessing and planning for the potential changes outlined above.
- *Solar Energy:* Solar energy has been in development for decades, but has never been economically competitive with fossil fuels, principally because of poor sunlight conversion rates and expensive installation costs. In recent years, a number of new technologies have been developed that may surmount both of these hurdles. These technologies are being funded by major government programs here and abroad, such as DoE's Sun Shot,[242] but increasingly invested in by large and small businesses who see growing, lucrative solar energy market. New solar cell technologies, such as quantum dots and crystals that allow multi-exciton dynamics,[243] could raise solar conversion efficiencies from the current 25% to a theoretical maximum of 42%, and perhaps to 70% with appropriate system engineering. Large scale deployment of novel, thin-film solar cell systems, for example by First Solar,[244] have dropped overall production costs to about $0.67 per watt, making it competitive enough for grid deployment. Several research groups have recently developed cheap, printable, flexible solar cells, and a Stanford group has developed versions composed entirely of extremely rugged carbon nanotubes,[245] although their current solar conversion efficiencies are low.

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[240] See http://csis.org/publication/geostrategic-implications-unconventional-oil-and-natural-gas
[241] See http://globaltrends2030.files.wordpress.com/2012/12/global-trends-2030-november2012.pdf, pp. 35-37
[242] See http://www1.eere.energy.gov/solar/sunshot/index.html
[243] See http://cleantechnica.com/2013/01/30/super-efficient-solar-cells-possible-through-use-of-exotic-form-of-silicon-generating-more-than-one-electron-hole-pair-per-photon/
[244] See http://www.firstsolar.com/
[245] See http://www.technologyreview.com/news/506901/all-carbon-solar-cells-will-mean-cheap-and-flexible-solar-panels/

The U.S. military has already become a leader in testing and deploying solar power, from large scale installations to tactical level devices for individual soldiers and vehicles,[246] part of a plan to deploy 3 Gigawatt or GW of renewable energy by 2025. Helping to develop and deploy the more advanced solar technologies mentioned above would give DoD much more bang for the buck, and additionally help keep this technology base in the United States, since it is being increasingly threatened by foreign competition. Current estimates are that the solar energy market will be about $15 billion by 2016 in North America, and about $75 billion globally, [247] and many nations are now attempting to commercialize and deploy solar technologies, most notably China.

- *Biofuels:* Biofuels, generally, are biological substances either naturally occurring or processed that are used as an energy source. There are a very wide variety of existing biofuels used globally, from burning wood and waste products, to liquids and gases produced from biomass using simple or more exotic chemical reactions. Most biofuel sources are not viable as a large scale energy source because of limited feed stocks; however, a few are now contributing at significant scale.[248] Most notable are ethanol fuels produced from various feed stocks such as corn and sugar cane, which currently make up a few percent of the liquid fuel sources in the United States. These particular biofuels, however, have had the unintended effect of raising food prices in some regions, with some resulting political backlash. Using cellulose-based feed stocks could alleviate much of this source competition and widen the potential base of stocks; however, it has proven much more difficult to develop the chemistry necessary to convert cellulose efficiently. Still, biofuels currently make up almost 3% of the transportation fuels used globally, and they are growing by about 6% per year, almost twice the rate of fossil based fuels.[249]

  Several recent technology advances could make biofuels much more competitive and plentiful. Genetic engineering of plants, in particular, switchgrass, so that their cellulosic components are easier to process into biofuels has been demonstrated by a number of groups. [250] Genetically engineering bacteria to be able to digest a variety of cellulosic materials has also been recently demonstrated.[251] Algae, including genetically engineered versions, are a promising route to significantly improved processes for converting a range of feed stocks to biofuels, and a number of companies have recently invested hundreds of millions of dollars in several large scale pilot plants.[252] In April of 2013, DoE also announced the award of almost $18 million in matching funds for four different pilot biorefineries to create drop-in fuels for automotive, naval, and aviation use.[253]

  DoD has several major activities aimed at developing biofuels as alternative fuel sources, such as the Great Green Fleet demonstration, part of a $510 million interagency effort to

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246 See http://www.solarnovus.com/index.php?option=com_content&view=article&id=5763:us-military-support-for-solar-energy&Itemid=352

247 See http://www.marketsandmarkets.com/PressReleases/solar-energy.asp

248 See Dr. Tim Coffey, A Primer on Alternative Transportation Fuels, NDU, CTNSP, Sept 2010, which looks at the cost of producing various kinds of alternative transportation fuels at scale. http://ctnsp.dodlive.mil/files/2013/07/DTP-074.pdf

249 See http://www.grida.no/graphicslib/detail/world-biofuels-production-trends_d3ec

250 See http://arstechnica.com/science/2011/02/get-ready-for-gmo-biofuels/

251 See http://www.huffingtonpost.com/2013/03/28/genetically-modified-bacteria-ka-yiu-san_n_2972556.html

252 See http://gigaom.com/2013/01/17/2013-could-be-a-make-or-break-year-for-algae-fuel/

253 See http://www.renewableenergyfocus.com/view/32112/us-energy-department-announces-projects-to-develop-advanced-drop-in-biofuels-for-military-jets-and-ships/

develop these fuels, and also plans to spend about $300 million to purchase biofuels over the next 5 years as an early adopter.[254] However, at a current cost of roughly ten times that of petroleum, these efforts recently drew Congressional criticism.[255] With an austere budget outlook for the foreseeable future, and the prospect of decreasing oil prices as shale gas reserves are tapped, it is unclear whether biofuels will continue on a trajectory to become economically competitive within this decade.

- *Batteries:* Batteries are an enormously important technology across a range of application areas, from large scale storage to small scale devices, and they are important technology for industrial, personal, and military uses. Much research has gone into improving battery technology over several decades, but energy densities have historically improved relatively slowly. However, as mobile electronic devices continue to proliferate and electric cars are being commercialized, the global market for batteries is accelerating, and expected to reach $144 billion by 2016.[256]

  A number of exotic new battery technologies are now in development or already being commercialized. Successors to the current lithium-ion battery include lithium-air batteries, magnesium or aluminum-ion batteries, and electrolyte flow batteries.[257] A number of new battery technologies are also in development that make use of nanotechnology or nanomaterials, for example lithium-ion batteries enhanced by nano-tin crystals, [258] or a silicon-graphene matrix.[259] These enhancements can dramatically improve energy densities, battery life, and re-charge times. One notable case was the Nanophosphate™ battery technology created by A123 Systems,[260] which had excellent performance and was to go into mass production in 2012. A123 became financially troubled, however, and in early 2013 was sold to the Chinese conglomerate Wanxiang America, despite considerable public criticism in the United States. Another cutting-edge technology is flexible, thin films that are solar panels as well as batteries,[261] in which China has been investing considerable resources.

  Significantly enhanced battery technologies will not only improve the operational characteristics of electronics and communication devices, but will facilitate wholly new large scale systems, such as operationally viable all-electric vehicles, large scale storage for solar and wind power, and mega-scale storage for the electric grid. DoD has been funding various programs to develop next generation batteries, for example, Defense Advanced Research Projects Agency (DARPA) programs developing nanomaterial enabled batteries,[262] or hybrid

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[254] See http://www.nationaldefensemagazine.org/archive/2012/June/Pages/BiofuelsIndustryatCrossroadsasMilitaryWaitsforLowerPrices.aspx
[255] See http://www.nytimes.com/2012/08/28/business/military-spending-on-biofuels-draws-fire.html?pagewanted=all&_r=2&
[256] See http://www.prnewswire.com/news-releases/global-battery-market-forecast-to-reach-usd144-billion-in-2016-175444421.html
[257] See http://www.economist.com/news/science-and-technology/21571117-search-better-ways-storing-electricity-hotting-up-batteries
[258] See http://phys.org/news/2013-04-tin-nanocrystals-battery-future.html
[259] See http://gigaom.com/2011/11/16/future-gadget-batteries-could-last-10-times-longer/
[260] See http://thinkprogress.org/climate/2012/06/12/498076/troubled-battery-maker-a123-unveils-breakthrough-new-lithium-ion-technology/?mobile=nc
[261] See http://www.globalsources.com/gsol/I/Solar-cell/a/9000000118833.htm
[262] See http://www.popsci.com/technology/article/2010-10/future-li-ion-batteries-will-be-smaller-grain-salt

battery/ultracapacitor systems.[263] Additionally, the U.S. Army has two battery labs under the Tank Automative Research Development and Engineering Center (TARDEC). [264] The Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) also funds a number of advanced battery programs, and in the private sector, the U.S. Advanced Battery Consortium[265] is coordinating development of next generation battery, ultracapacitor, and fuel cell technologies across sectors. These significant improvements in energy storage technologies, most likely to be commercialized within the next 5 to 10 years, will have considerable impact on U.S. military systems, including the individual warfighter, vehicles, drones and unmanned vehicles, as well as large scale storage for enhancing solar or wind power facilities.

- *Hydrogen Storage and Fuel Cells:* The prospect of a future hydrogen economy has been a long-term goal of the United States and other nations for years, including being a priority of the last Bush Administration. Combining hydrogen generation and storage technologies with fuel cells to provide electric or thermal power has been studied extensively in technological, engineering, infrastructure, and economic aspects. While much of the capability exists or is feasible, a number of significant technological hurdles remain. Major Federal programs are tackling these problems, for example at the DoE National Renewable Energy Lab (NREL) Hydrogen and Fuel Cell Office [266] and Energy Efficiency and Renewable Energy (EERE) Fuel Cell Office, and in a wide range of domestic and foreign universities and companies.

  Several recent technological developments are bringing hydrogen-based energy systems much nearer. MIT researchers have developed an Artificial Leaf, [267] a cheap silicon/cobalt/nickel chip that splits water directly into hydrogen and oxygen using sunlight. In 2012, Australian researchers developed a nano-enabled form of sodium borohydride that has a very large hydrogen storage capacity, and also safely stores and releases energy within a moderate temperature range.[268] Ford, Daimler, and Nissan recently announced they are teaming to bring an advanced fuel cell drive train system for vehicles to market by 2017,[269] prompting Toyota and BMW to follow suit.

  DoD has been a major developer of fuel cell technology for a decade or more, and fuel cells could provide a wide range of power sources, including tactical level power, vehicles, direct and backup power for facilities, distributed generation, and power for unmanned vehicles.[270] With recent technological breakthroughs and major commercialization and deployment efforts by large corporations, however, highly capable commercial-off-the-shelf (COTS) technologies will likely be available within 5 years time, which may be a better DoD investment for most routine power applications.

- *Energy Harvesting:* Energy harvesting or "scavenging" is one of the more novel and potentially important energy technology areas now developing. It involves collecting low

[263] See http://www.smartplanet.com/blog/intelligent-energy/darpa-funds-17-million-for-new-ultracapacitor/4231
[264] See http://www.whitehouse.gov/the-press-office/2012/04/11/fact-sheet-obama-administration-announces-additional-steps-increase-ener
[265] See http://www.uscar.org/guest/view_team.php?teams_id=12
[266] See http://www.nrel.gov/hydrogen/proj_storage.html
[267] See http://www.cnn.com/2014/04/28/tech/innovation/the-artificial-leaf-power-solar-electricity/
[268] See http://www.sciencedaily.com/releases/2012/08/120815093303.htm
[269] See http://www.economist.com/blogs/schumpeter/2013/02/hydrogen-powered-cars
[270] See http://www.fuelcells.org/wp-content/uploads/2012/02/LMI-Fuel-Cell-Report.pdf

level background or waste energy and utilizing it for useful applications. The low level energy sources can be thermal, mechanical, electromagnetic, acoustic, or even fluid flow, and collection technologies include small scale mechanical generators, piezoelectrics, photovoltaic cells, induction coils, ultracapacitors, or a variety of other devices. Generally, these systems also require energy storage capability, power conditioning or management elements, and a mode of transmitting the collected energy efficiently. A considerable amount of R&D is ongoing in these areas, including in Federal agencies such as DoE, universities, and a variety of companies, and there are a number of industry groups coordinating research agendas.[271]

Converging technology trends are making energy harvesting much more viable. One is that the energy requirements of many electronic devices and other systems are being reduced to the point where low level ambient energy is sufficient to power them. Another trend is that several new technologies are being developed that can efficiently harvest, store, and utilize the energy. For example, small printable antennas have been developed recently that can harvest ambient electromagnetic radiation,[272] and Microgen Systems[273] is now developing a number of small integrated piezoelectric devices that can harvest background vibrations and convert it directly to electricity. Researchers at Wake Forest are developing a new flexible fabric made of carbon nanotubes in a plastic matrix that is very efficient at converting background thermal energy into electricity,[274] and the Auckland Bioengineering Institute is developing a suite of highly efficient human biomechanical energy harvesting devices based on electrically driven elastomer membranes.[275] At a larger scale, several existing technologies already can harvest waste heat, for example from near power plants, which could be deployed on a much wider scale.

The U.S. military has funded a number of research programs on energy harvesting over the last decade, and a number of pilot technologies have been tested or deployed; however, there are many additional opportunities for harvesting energy for small scale devices, such as for individual soldier power requirements, unmanned vehicles, and unattended sensors or distributed wireless sensor networks. Still, the rapid development of these technologies in the private sector may make COTS technologies available sooner for a wide range of mission areas.

- *Smart Power Systems:* Smart power systems generally refer to energy generating and delivery systems which are enhanced by information technology, including use of distributed sensors and data gathering, real time modeling, and advanced control systems. The smart grid concept being developed for the U.S. national electric grid[276] involves these technological innovations and will facilitate more efficient management, repair, and energy allocation, but also allow for use of a variety of distributed renewable energy sources and storage

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271 See http://www.energyharvesting.net/

272 See http://www.popsci.com/technology/article/2011-07/new-printable-devices-can-harvest-ambient-energy-power-small-electronics

273 See http://www.microgensystems.co/

274 See http://cleantechnica.com/2012/02/24/imagine-electricity-generating-clothes-but-without-solar-panels-on-them/

275 http://www.digitaltrends.com/features/batteries-not-included-how-small-scale-energy-harvesting-will-power-the-future/6/

276 See http://energy.gov/oe/technology-development/smart-grid

technologies, as well as self-healing resilience against disturbances or attack, and even ability to support the energy markets. Smart grid concepts and technologies are also easily applied to local or isolated power grids as well, such as in a military setting. Another application of smart power systems is to smart buildings.[277] Smart buildings sometimes refers to incorporating advanced materials such as insulation or green roofs; however, the novel technological aspects are the use of embedded systems throughout the building, use of appliances and heating and cooling systems, managed by a central computer system and sometimes incorporating SCADA control systems. In 2011, the Obama Administration launched the Better Buildings Initiative[278] to nationally coordinate the development and deployment of advanced technologies and standards for smart buildings. These efforts have significant implications for future U.S. energy use the DoE estimates that there are roughly 4.8 million commercial buildings and 350,000 industrial facilities in the United States that consume about half the country's total energy needs, and about 30% of this could be saved by optimizing energy use.

DoD has been given a mandate to improve its energy efficiency in a variety of ways by the Energy Security Act of 2011,[279] and many provisions pertain to buildings and facilities. In response, DoD currently has a goal of reducing its overall energy intensity by 30% by 2015, the Navy has a goal of having half of its bases being energy self-sufficient (i.e., "net-zero energy") by 2020, and the Army has implemented the strictest building standards in the Federal Government, with a goal of eventually having all its facilities at net-zero energy.

- *Directed-Energy Weapons:* One novel use of energy technologies is for DEWs, an area which has been in development since the 1960s. Such weapons emit pure energy in the form of electromagnetic radiation of some spectral range, for example, laser light or millimeter wavelength radiation. The advantages of such a weapon system have long been recognized, and include near-zero flight time, high accuracy, and a potentially infinite "magazine." DoD has had research programs and facilities developing directed-energy technologies for many years, in particular within the Navy.[280] There have also been a number of significant advancements in recent years in the ability to aim, mount, and operationally integrate such weapons, in particular, lasers.[281] The Navy deployed its first laser weapon on the USS Ponce in mid-2014.[282] However, a serious hurdle at present is the ability to generate enough energy to make the weapons very effective. Most current systems are an order of magnitude or more weaker than would be minimally desirable, although all the armed services and DARPA currently run research programs aimed at reaching dramatically improved power levels by about 2020.
- Once DE weapons are fielded, however, there is little doubt that they will dramatically change battlefield dynamics.[283] They will likely require the development of new doctrine and

[277] See http://www.triplepundit.com/2013/02/smart-building/
[278] See http://www.whitehouse.gov/the-press-office/2011/02/03/president-obama-s-plan-win-future-making-american-businesses-more-energy
[279] See http://thinkprogress.org/climate/2011/06/14/244716/military-renewables-efficiency-and-energy-security/
[280] See http://www.navsea.navy.mil/nswc/dahlgren/NEWS/directed_energy/directed_energy.aspx
[281] For example, see http://www.popsci.com/article/technology/army-truck-shoots-drones-mortars-lasers?dom=PSC&loc=recent&lnk=1&con=army-truck-shoots-drones-mortars-with-lasers
[282] See http://rt.com/usa/navy-warfare-laser-ponce-454/
[283] See: http://www.csbaonline.org/publications/2012/04/changing-the-game-the-promise-of-directed-energy-weapons/

operational strategies, and some feel that they could redress the increasing parity of other nations and non-state actors with the United States, entities who can, for example, leverage cheap drones. Some forms of DE weapons also provide unique non-lethal capabilities that can create new options for force protection and civilian applications.

National Security Implications: Energy availability is at the core of modern society, and energy security will continue to be a national priority in the coming decades. A focus on demand reduction and incorporation of energy considerations in to DoD business practices is the place to start. The development of a broad spectrum of energy sources and smart infrastructure is a judicious path for the United States; however, the release of vast stores of fossil fuels from shale deposits remains a wild card, and may in fact mean that major investments in some alternative energy technologies should reasonably be delayed, as they become less economically competitive in the near term. This general investment scenario will likely hold for DoD as well, particularly as it attempts to maximize efficiency during future budget constraints. However, development of new technologies for smaller scale systems, such as solar energy plants for facilities and energy harvesting for individual soldiers, will likely remain a high impact investment.