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Commentaries

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Emerging Technology

Creator of Worlds

Many readers of *Strategic Studies Quarterly* will no doubt remember lyrics from the song "In the Year 2525," released in 1969, written and composed by Rick Evans. For younger readers who do not remember this somewhat prescient melody consider these few lines:

Everything you think, do and say
Is in the pill you took today. . . .
Your arms are hangin' limp at your sides
Your legs got nothin' to do
Some machine's doin' that for you. . . .
You'll pick your son, pick your daughter too
From the bottom of a long glass tube…

In the year 2016, many of these predictions have either come true, are in progress, or surely will materialize within the next 509 years. Throughout history, mankind has maintained the desire to continually expand the bounds of science and nature in search of something new—sometimes benefitting the species, at other times threatening it. Just as the nuclear revolution led to advances that would threaten the world, it also created opportunities to benefit mankind. Twenty years after the first use of a nuclear weapon, Robert Oppenheimer recalled his feelings about it, quoting from the *Bhagavad Gita*, "Now I am become death, destroyer of worlds." Today, one can imagine, indeed, expect and rely on science to proclaim: "Now I am become life, creator of worlds." Similarly, from nuclear weapons to nuclear medicine, current emerging technologies offer many of the same challenges and opportunities.

Consider for a moment several technologies from 20 years ago that are no longer emerging but, rather, mature and commonplace: stealth, precision, and machine automation, among others. Each of these has had a significant effect on defense, economics, and national security. In some cases, such as stealth, the effects have been especially profound, creating defense capabilities that match the dreams of airpower pioneers. In the case of machine automation, the impact transformed production for many heavy industries, yet at the same time decreased the overall need for human capital.

Surveying current emerging technologies, one finds the world is experiencing even more profound uses. Artificial intelligence, brain interface, robotics, autonomous systems, biotechnology, lasers, hypersonics, and additive manufacturing (AM) are the most prominent examples. In every case, science is pushing the limits of known capabilities or standard uses in its search for the full realm of possibilities. The partnership among science and creativity has already produced remarkable results. For instance, Google's recent computer win in the game of "Go" against a master human player indicates how far artificial intelligence has progressed. In robotics, one need look no further than most technology conferences to see fully functional robotic mules, dogs, and even "humanistic droids" able to complete a myriad of manual tasks. Not to be outdone, there now exist large and small semiautonomous drones and self-driving cars.

In the world of physics, enhancements in emerging technology manifest themselves in new capabilities, including lasers, quantum computing, and light physics. We are using lasers for help in correcting delicate vision problems and, in other uses, burning holes in metal objects or stopping moving vehicles. Even more impressive is the recent discovery of gravity waves. While the science is still evolving, eventually this discovery has the potential to change what we perceive as time, space, and matter.

Another technology that continues to emerge is AM, using a printer to create three-dimensional items. Over the past five years, companies like 3D, Organics, and Stratasys have pushed the boundaries of all traditional manufacturing techniques to produce items from a machine originally conceptualized as capable of only one dimension. The idea has progressed from printing simple, crude machine parts to creating items as durable as houses, to those as delicate as human tissues, including skin. The extent of how far this technology has emerged is evident by comparing the small plastic computer cases first produced by AM to the Chinese houses being printed today. While many uses of AM are beginning to emerge, such as onsite parts manufacturing for enhanced logistics, much greater uses are on the horizon. One can imagine the possibilities this technology can and will have in other areas—particularly if combined with other disciplines. For instance, in theory it would be possible to combine advances in biotechnology, nanotechnology, and quantum computer technology to "print" new life.

Creator of Worlds

It is in the fields of biology and medicine, however, that emerging technologies will make the most profound advancements in life as we know it. Ever since the Human Genome Project mapped human DNA and discovered all humans are 99.9 percent alike, science has been attempting to decipher the more important statistic—the remaining 0.1 percent. Already the science of medical treatments has the capability to create customized medical treatments using biotechnology, particularly in treating certain types of cancer and a variety of other ailments. Emerging technologies are also enhancing human abilities in the form of protection, strength, and wellness. The next logical step will be human enhancement starting from the cellular level. In fact, the Chinese continue research on enhancing natural intelligence through manipulating the genome with the goal of a 20 percent increase in brain function and measured intelligence. This conceptual shift will deliver results far beyond what we know today as artificial intelligence. Soon the milestone of Google's computer win at the game of Go will seem elementary compared to what will be called designer intelligence. Thus, human enhancement will become most important to the future of mankind. Such advancements are already out of the planning stage and into the demonstration and usage stages—with achievements in neuroscience, biology, and immunology. In the near future, science will be able to harness the power of the genome to correct, enhance, and create advanced forms of life. These breakthroughs will produce new challenges and new opportunities. One challenge will be to define what is considered human, ultrahuman, or subhuman. Another will be how far science should be allowed to push the boundary of normality while respecting shared notions of ethics and morality. Still another will be the question of whether to engage in the same activities as other nations or rogue scientists who do not respect limits on human enhancement. Regardless the choice or answers, the fact remains that science will evolve and unlock even more potentially harmful aspects and even greater healing opportunities.

One opportunity available will be the ability to overcome disease as we know it. In fact, these breakthroughs will allow science to redefine what is disease—that caused by nature, or that left untreated by science. Here is where the power of individual choice will become an imperative, because one will be able to choose enhancement or corrective therapy to change human conditions such as appearance, intelligence, gender, or even sexual orientation. In the same way that science will redefine disease, society will redefine what is normal for a human being based on the realm of the possible. While the thought of artificial intelligence and human enhancement is frightening to many scholars and scientists, the irony of the future is enhanced human beings will be needed to provide controls over artificial intelligence and the machines produced by it.

Ethics and Emerging Technologies

Finally, no discussion of emerging technology would be complete without considering the ethical dimensions of the future. Several arguments emerge, on both sides of the issue, including lifesaving versus life-altering treatments, the progressive slippery slope of emerging technology, and intended versus unintended consequences.

Even in the medical community there is great debate over how far life-altering treatments should progress. On the optimistic side, many physicians and researchers see promising opportunities to prevent, reverse, or eliminate several debilitating conditions. The ethical argument becomes one rooted in traditional ethical teachings: one who has the power to save lives, prevent suffering, or mitigate damage and chooses not to do so makes an unethical choice. Those opposed tend to focus on the difference between treating disease rather than simply altering or enhancing what nature has provided. Is *normal* whatever nature provides, or is *normal* whatever is possible with what nature provides? This thinking leads to the second argument of a progressive slippery slope. The fear is "if this, then this," assuming that if science is allowed to correct certain nuisance conditions, the result will lead to inevitable lax standards and evil ends. For example, a recent issue of *Smithsonian Magazine* asked the question, "The Last Mosquito?" Scientists have the capabilities to eradicate most—if not all—species of mosquitos responsible for malaria, dengue fever, and the Zika virus. Should they? If the world decides to do so, then perhaps rats and mice should be next. And which species will be eradicated after those? Some or most of the gene-altering capabilities can surely apply to the human species as well. While there are two sides to this argument, the answer is not mutually exclusive. If it were, the world would still be fighting most of the now-extinct childhood diseases, which relates to the third argument—unintended consequences. Many of the vaccines of the early twentieth century were results of trial and error. In some cases, those trials produced great error, and even today, no vaccine is 100 percent safe, as we know from the few yearly deaths among those first immunized. As much as any science begins with great knowledge and a sound theory, it can only be fulfilled by trial and error—in essence, repeatable demonstrations. Emerging technologies are no different, and the ethical concerns mirror those of earlier risk periods in our history. Prudence dictates that researchers proceed with caution, but proceed they must.

While the analogy to nuclear weapons holds certain similarities, those for emerging technology will be somewhat different. The world once learned to ban chemical weapons, after nightmarish use on a large scale. Nations eventually learned how to produce arms control agreements and nonproliferation agreements for nuclear weapons and nuclear materials. However, the learning curve for this new destructive power was quite steep, and the technology has not been banned. Humanity also decided against the use of biological weapons with formal conventions, even though not all nations subscribe. Each of these scenarios provides examples of how destructive, blatantly aggressive, inhumane technologies can be controlled or eliminated. However, how does one deal with technologies that merely enhance human performance, intellect, immunity, or capacity? While they provide a distinct advantage, they do not necessarily present the kind of immediate threat of earlier weapons. Thus these will be more difficult to identify, control, restrict, and prevent.

Epilogue

The emerging technologies discussed in this article and the ones that follow are those that appear to offer the most promise for national defense. However, the technologies themselves do not provide the answers to strategic choice. For example, what tradeoffs must be made to afford such technologies, and how should the nation prioritize these opportunities? Current debates within the Department of Defense and the US Congress illustrate the tension between the realm of the possible and the reality of the necessary. While the United States cannot stop the procession of emerging technologies, not all technologies should find their way into national defense.

Many Western scholars, theologians, and scientists object to artificial intelligence, genetic modification, and human enhancement as somehow taboo. Our adversaries do not necessarily subscribe to this standard. Thus, the question for many will be whether we let our imagination, optimism, and dreams lead the way into the future or opt to be stymied by our fears. With its disparate views of ethics and morality and seeming lack of both, the world will find it hard to restrain the nature of man to explore, progress, and change as the science of emerging technology allows. SSQ

W. Michael Guillot
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The Emerging Life Sciences and the National Security State

In 2014 Secretary of Defense Chuck Hagel described a new "game-changing offset strategy" intended to counter a new generation of disruptive technologies being developed by China and Russia, innovations that could undermine US military advantages. Secretary Hagel's strategy has come to be known as the third offset, following in the line of the Eisenhower administration's "New Look" that emphasized massive nuclear retaliation and the Carter administration's "Offset Strategy" that led to precision-guided munitions like laser-guided "smart bombs" and computerized command-and-control systems. These technologies were cutting edge in their day, but in the past two decades possibilities have emerged that require new ways of thinking about defense research and development, particularly in the life sciences.

So far the concept of a third offset seems mainly to be a convenient handle for a menu of new defense capabilities, many based on the convergence of neuroscience and engineering. These novel capabilities include autonomous "deep learning" machines and systems for early warning based on crunching big data, human-machine collaboration to help human operators make decisions, assisted-human operations so that humans can operate more efficiently with the help of machines like exoskeletons, and advanced human-machine teaming in which a human works with an unmanned system.

Notably, all of these technologies involve a combination of applied neuroscience and engineering. For example, so-called *autonomous systems* may benefit from software that has been developed with improved knowledge derived from basic science about how the brain processes information. Although the brain is often called a computer, it is more accurate to say that the brain is an evolved biological system that computes while it adapts. The adaptive abilities of the brain are the salient properties that underlie deep learning and set it apart from artificial systems that have historically been "dumb," relying on their original programming. As a colleague at the University of Pennsylvania remarked to me a few years ago, Google has much more memory than humans do, but the software is not as good.

There is currently an argument not only about whether offensive autonomous weapons systems can be accountable but also whether they can be controlled (leaving aside all the technical and epistemological issues about the meaning of *autonomy* in this setting). A system capable of making suitably complex decisions independent of a human operator could challenge conventions about accountability. That is a solvable problem; presumably new conventions for the laws of autonomous armed conflict can be devised. Some have suggested that, far from creating new problems for commanders, these complex devices can have ethics rules built into their programming so they will be less likely to violate military ethics than humans. However, the philosopher Nick Bostrom, in his book *Superintelligence: Paths, Dangers, Strategies*, has argued that silicone-based machine intelligence is not only inevitable but inherently quite dangerous, whether in the context of armed conflict or not. An intelligent machine that is equipped with adaptive deep learning could both program itself and develop other machines it could integrate into its system, thereby vastly expanding its computational capacity to the point that it would achieve what Bostrom calls superintelligence. Suppose such a device were to develop certain goals that would serve the completion of its computational task—for example, the solution of a seemingly impossible mathematical problem. In that case it could in principle subjugate every bit of matter on Earth—and perhaps beyond—to the job of information processing. Such an outcome would mean not only that human beings would be entirely dependent on the superintelligence for their survival but could lead to the end of human life itself.

This doomsday scenario is met with skepticism among computer scientists—who regard their devices as exceptionally vulnerable to hacking, plug-pulling, or even a swift kick—and by biologists, who do not believe any inorganic system can master all the skills of even a fairly simple biological brain. By contrast, human-machine collaboration is already here, from iPhones pulling information off the cloud to augmented, reality-equipped visors to military pack animals like Boston Dynamics' "Big Dog" (though the prototype needs to get a lot quieter to be viable for its intended purpose). But these devices require the use of eyes and hands and entail some delay in response. Some medical devices are implantable and respond immediately, such as intracardiac defibrillators for patients at risk of heart attack and cochlear implants for those with hearing impairments. In neuroscience, strides have been made with brain implants to relieve symptoms of movement disorders and perhaps even depression. Currently these chips have only 96 electrodes, but the Defense Advanced Research Projects Agency (DARPA) is supporting work on a new implantable array for brain implants that would include hundreds of thousands of electrodes. Clearly, advances in material science will be required to achieve that goal, but if these super neural chips can be developed and safely introduced into the brain with reliable results—all very high bars—the relationship between an operator and a machine will be utterly transformed (think Clint Eastwood's robotic airplane in the film *Firefox*). At that point we would be led to ponder important questions about the nature and limits of the human being in relation to the machine.

Not all neurotechnology-related developments entail such a high level of advanced science or engineering. According to some, improved decision making and accelerated learning can be achieved with relatively simple neural stimulation devices used in the right way. A number of studies have reported that a painless technology called transcranial magnetic stimulation (TMS) can improve visual perception in healthy people.[1] In TMS, a magnetic coil is placed above the head, and electrically produced magnetic pulses pass through the cortex. These pulses can alter the firing rate of certain neurons. Researchers hope that TMS may someday be used to treat stroke patients or those with dementias or depression. Research also suggests that TMS could help healthy people benefit from better-than-normal visual perception. The military application is provocative: soldiers on reconnaissance duty, snipers, or fighter pilots operating in target-rich environment could benefit. A 2009 National Research Council (NRC) report, *Opportunities in Neuroscience for Future Army Applications*, lists in-helmet and in-vehicle TMS as long-term projects to keep on the research and development radar.

Of course, in the twenty-first century, national security strategists face a multipolar world that also includes nonstate actors capable of terror attacks that pose mainly a psychological rather than an existential threat. Some technology disruptors are, in the language of a 2014 NRC report, "emerging and readily available."[2] To use one example, the cheaper cousin of TMS, called transcranial direct current stimulation (tDCS), might turn out to be just as beneficial in improving cognitive abilities as TMS. All tDCS requires is a 9-volt battery and a couple of electrodes.[3] Enhanced cognition might also be accomplished with new and better pharmaceuticals. A trailblazer in this regard is modafinil, the generic form of the antisleep stimulant marketed as Provigil that is already approved for use in the Air Force. In a different vein, terrorist organizations and conventional militaries would like to be stronger and faster. There is no reason in principle why prosthetic devices like exoskeletons and artificial limbs could not improve or even replace physical functions. Terrorist groups might not be as inhibited as conventional forces about recruiting fighters to undergo deliberate amputation for the sake of significantly improved performance.

Especially in the context of terrorism, looming in the background are variations of the age-old problem of biosecurity. Since ancient times, and even in the biblical account of the plagues unleashed against pharaonic Egypt, microorganisms have represented a special kind of scourge. In the American war for independence, George Washington worried that the British were spreading smallpox in Boston, and during the Civil War, Confederate forces dropped horse carcasses in wells as they retreated from Union armies. Modern biology poses new opportunities to add to the list of select biological threat agents. Synthetic biology uses engineering principles to create new biological entities. Cells can be engineered to perform novel functions and provide new drugs, materials, and energy sources. Besides unintended consequences, they may also be designed to be harmful to humans, animals, and the environment. Increasingly, any bright high school biology student can master "synbio" techniques, and the cost of the raw materials like yeast and *Escherichia coli* (*E. coli*) is dropping rapidly.

Besides synthetic biology—which generally builds DNA molecules out of smaller parts—powerful and efficient new laboratory technologies grouped under the heading of *gene editing* use an ancient biological system to modify strands of genes with great precision. Gene editing techniques like clustered regularly interspaced short palindromic repeats (CRISPR)/cas9 are already being used in agriculture and can modify genes in pests like mosquitos to render them infertile. Using these techniques, genes have been inactivated in human cell lines in the laboratory, but experiments on human beings are not permitted by any national regulatory system.

What is especially remarkable and controversial about gene editing is the fact that the DNA in fertilized human eggs can be modified in germ cells so that novel traits can be inherited. Previously human germline modifications have largely been viewed as unethical, unlike modifications in somatic or body cells of an individual. These techniques bring germline changes closer to practical reality. There are plausible arguments for eliminating, say, breast cancer-related genes. The techniques also stimulate visions of armies made up of "designer soldiers." However, apart from the fact that no one can predict the results of such experiments (genomes are of vast complexity and their manifestations depend on environmental triggers that cannot be factored in with confidence), the payoff for an aggressor would be nearly two decades in the future, and before that, concealment of the project would prove very difficult. Such science-fiction scenarios are compelling, but from a security-planning standpoint, they are ludicrous.

Of more immediate interest is the need to bring certain neurotechnologies under extant international conventions as "dual use," research that can be used for malign as well as benign purposes. TMC and tDCS are among the most likely neurotechnological candidates for consideration in the periodic revisions of the Biological and Toxin Weapons Convention (later in 2016) and the Chemical Weapons Convention (2017). As well, "calmatives" for crowd control—such as the opioid carfentanil—have been used by Russian special forces and have attracted the attention of the US military. Of interest to interrogation operations, neuroeconomists have studied the usefulness of the artificially introduced brain hormone oxytocin to enhance trust. The Briton Malcolm Dando and his colleagues have taken the lead on bringing these issues to the attention of the convention revision bodies, while my former post-doctoral fellow Nick Evans and I have initiated a project to catalogue these other neurotechnologies that are candidates for regulation.

Finally, I offer a word about the changing politics and sociology of national security research. Discussions about national security and science usually focus on the physical sciences and engineering, but the life sciences, including biology and the social and behavioral sciences, have played a distinctive role in defense and intelligence research and development. Especially in the past 50 years, these sciences' fortunes have ebbed and flowed depending on political events, cultural trends, and developments in the sciences themselves. In the late 1960s, much social and behavioral science undertaken on behalf of national security agencies was seen as politically objectionable and moved away from university campuses to contract research organizations. Especially in the case of cultural studies of problems like communist insurgency, some argue that the result was an inherent conflict of interest, with paymasters getting the answers they wanted and research receiving inadequate peer review. But social and behavioral sciences are increasingly converging with basic physical science. Developments such as those described here in fields like genetics and neuroscience have brought much of this activity back to campus and appear to be the leading edge of a new era in the academic-industrial complex and the national security state. SSQ

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Notes

1. See, for example, Michael L. Waterston and Christopher C. Pack, "Improved Discrimination of Visual Stimuli Following Repetitive Transcranial Magnetic Stimulation," *PLoS One* 5, no. 4 (28 April 2010): 1–10, doi: 10.1371/journal.pone.0010354.
2. Jean-Lou Chameau, W. F. Ballhaus Jr., Herbert Lin, and National Research Council, *Emerging and Readily Available Technologies and National Security: A Framework for Addressing Ethical, Legal, and Societal Issues* (Washington, DC: National Academies Press, 2014), ix, doi: 10.17226/18512.
3. Alexandre F. DaSilva, Magdalena Sarah Volz, Marom Bikson, and Felipe Fregni, "Electrode Positioning and Montage in Transcranial Direct Current Stimulation," *Journal of Visualized Experiments* 51 (2011): e2744, doi: 10.3791/2744.

Brain-Machine Interfaces: Realm of the Possible

On 28 November 2014, Jan Scheuermann fed herself a bar of chocolate at the University of Pittsburgh Medical Center. For most of us, this would not be a newsworthy event. But for Jan, who is paralyzed from the neck down, it was a major milestone. She was able to command the Modular Prosthetic Limb (MPL) with her thoughts alone to grasp the chocolate bar and feed herself for the first time since becoming paralyzed. The video of the event is beautiful and awe-inspiring not only for its moment of independence and joy but also for the incredible technological achievement that made it possible.[1] Jan is one of the early pioneers of a brain-machine interface (BMI), which is opening new doors for many applications.

Before Jan there was Tim. By controlling an MPL with his thoughts, Tim was able to reach for and touch his girlfriend's hand for the first time since being paralyzed in a motorcycle accident.[2] Beyond the technical accomplishments, both of these demonstrations show the potential for humans to interact with a robot in ways that are very different. The smiles and tears testify to a very human-like connection with the machine.

Mind over matter is now a phrase that is closer than ever, thanks to advances in BMIs. Imagine not being able to move an arm or leg. Even though you can visualize it in your mind, your body is not able to comply. A study by the Christopher and Dana Reeve Foundation found that nearly 1 in 50 people in the United States—almost six million people—are living with some type of paralysis. Leading causes include stroke, spinal cord injury, and multiple sclerosis. For our service men and women, the conflicts in Iraq and Afghanistan have emphasized the potential of these technologies to address combat injuries that result in amputation. Remarkable advances in combat casualty care have resulted in survival rates that surpass any other conflict, and warfighters are surviving severe injuries that often require extensive rehabilitation and support. Often in their early twenties or even still teenagers, these men and women have a lifetime ahead of them, and many want to continue to serve. Beyond the heavy emotional toll on those affected and their caregivers, tens of billions of dollars are spent caring for these individuals every year. But new technologies are bringing new hope, and recent advancements in BMIs demonstrate potential avenues for addressing some of these pressing challenges.

With these challenges in mind, the Defense Advanced Research Projects Agency (DARPA) started the Revolutionizing Prosthetics Program in 2005. The program is an investment in a wide range of neurological and rehabilitative technologies to address the most challenging of these combat-related injuries, and it focused on two objectives. First was the creation of the MPL, the world's most advanced prosthetic arm.[3] The second was to create an interface for the MPL with the human brain so the user could interact with the prosthesis with the same dexterity and feeling as a natural limb and with little conscious thought. To create this interface, small electrodes were placed on the surface of Jan's brain to measure electrical impulses when she thought about moving her arm. Then those signals were decoded and translated into commands to the MPL. Despite the complexity of the technology, to Jan, it was as simple as moving her arm.

Applying these technologies to move a prosthesis is awesome and emotional in reconnecting people with the world. But until recently, that brain-machine connection was one-way—the brain reaching out through the machine, with no feeling or feedback in return. A confluence of technical advances is extending BMIs so that the MPL can communicate back to the brain. Our ability to perceive our environment is as important as—or perhaps even more important than—our ability to move a limb. A major complaint of prosthetic users is the need to look at the prosthesis while using it. Simple tasks like holding a glass and taking a drink with eyes closed are nearly impossible with conventional prostheses. Without a sense of touch and proprioception (knowing where your arm is in space without actually seeing it), simple tasks become extraordinarily difficult. It is a bit like trying to talk after being numbed during a dental appointment. If you cannot feel your mouth, it is difficult to speak clearly. Today, science is beginning to move past this barrier. For example, amputee Johnny Matheny can perceive stimulation of certain nerves as coming from his prosthetic fingers and hand (known as haptic feedback), enabling him to identify objects using sensors located on the fingers of the MPL.[4]

With such potential, BMIs should eventually allow people to communicate with robotics in a more natural, intuitive way. Recent research demonstrates that it may be easier than ever. For example, after Jan spent two years practicing with the arm, we asked the question, "Could she adapt her ability to move the MPL to a very different device?" To test this, we decided to ask Jan to control an aircraft in a flight simulator. We simply unplugged the MPL and connected a flight simulator that was adapted to convert wrist motions to the motion of a joystick.[5] Although she never had flown a plane, she was able to rapidly achieve level flight and progressed to doing a series of simulated maneuvers and flight patterns, including flying through the Grand Canyon. Amazingly, when asked how she was controlling the aircraft, she told us that, at first, she visualized wrist motions, but she quickly transitioned to just visualizing how she wanted the plane to move, without thinking of her wrist. Furthermore, she described this as one of the most enjoyable experiences she had during the two-year study.

Connecting these individuals with the world, through these machines, is an incredible privilege, and, although the technology is still in its infancy, these applications offer a vision of how we all might be impacted by BMI advances. For decades, the challenge in getting the best synthesis of a human's and a machine's strengths has been the method by which they interact. Take, for example, a specific challenge: texting while driving. It is not that you cannot think of the message that you want to send. It is not that the phone is not perfectly capable of sending the message. The problem is that you must physically interact with the phone—the point of interaction is the problem. Advances in voice recognition help remedy this situation, but not all human-machine interface problems can be solved by voice command. Furthermore, the power of the human mind lies in its ability to process information in parallel, whereas most human-machine interfaces require serial input. If we suddenly need to take evasive action while driving, an experienced driver can assess the situation and implement a course of action almost instantaneously. Now imagine that you had to communicate these instructions by keyboard or voice. Likely a crash would occur before you could communicate your intent.

What Else Can Be Done?

With the promise of BMI technology to solve human-machine interface challenges, the question inevitably arises: What else could be done? How can these advances contribute to national security? Although it might be too soon to begin planning for BMI in everyday life, it is not premature to begin imagining how the technology might be used by the nation. For the military, the first and most obvious application of this technology is to our wounded warrior community. Commercial devices to restore hearing and sight are already available, and the DEKA Research and Development Corporation's Luke Arm (developed by DARPA) is the most advanced Food and Drug Administration-approved prosthetic arm.[6] While today's applications show great promise, they could go much further. Wearable robotics such as SuitX's Phoenix exoskeleton aim to replace wheelchairs and could integrate BMI.[7] Today's wearable robotics require wearers to use residual capabilities, such as hands and arms, to walk, sit, or stand and are often not intuitive to operate.

Apart from rehabilitation, BMI could also dramatically revolutionize command and control. Thanks in part to the convergence of BMI, that revolution would come with two other technical trends. The first is the proliferation of data and devices used in greater numbers in increasingly complex situations. The second trend is the rapid advancement of artificial intelligence (AI).

For the first trend, we are now able to build more sensors and devices to inform our fighting forces, but the information can easily overcome the ability of the operator to access, analyze, and understand that data—and the machines that contain it. Information critical to mission success can be overlooked because there is so much of it, from weather reports, to radio frequencies, to historical context, to situation awareness. Making the challenge all the more difficult is that, even with all the information, it is difficult to know what to do with it. Furthermore, conflict is increasingly fought in a gray zone, where the distinction between civilian and combatant is (sometimes intentionally) blurry and the actions of one small unit can have broad-reaching or even strategic effects.

For the second trend, the advancement of AI, one of the most interesting research areas today investigates the possibilities of combining the advancements in BMI with advances in AI. Consider, for example, how you hold a coffee cup while having a conversation. To take a drink you must make fine adjustments to keep the cup level, prevent it from slipping, and bring it to your mouth. These actions require complex coordination between multiple muscles, yet you hardly give it a thought. Today's BMIs require conscious control of each action, while much of what we do naturally is a subconscious or learned response. As an example, learning a new task such as swinging a golf club initially requires thinking about how to hold the club, position the shoulder, adjust your stance, and so forth. After many hours of practice you no longer think about these low-level tasks. You concentrate on where you want to hit the ball to best position yourself for the next shot. Today's BMIs enable individuals to move each joint very naturally but are not capable of capturing the learned response associated with a complex action. This is where AI could excel. Using a BMI, a person could tell the machine what action to perform, and the AI could perform the lower-level functions, freeing the human to concentrate on decision making.

Advances in computing and AI have produced amazing results, but AI still faces fundamental limitations. The best AI systems (like Google's AlphaGo) still require extensive training. They must process information exhaustively, and they cannot generalize knowledge beyond a specific situation. As a result, AI is suboptimal and its application is limited by current technical constraints and policies that restrict its employment. But where AI is deficient today, the human mind excels. They are ideal partners, except for the fact that they do not work well together through the narrow choke point of the human-machine interface. If they could be efficiently coupled, we would have great possibilities for superior decisions and efficient command and control.

Technical and Ethical Questions

While the technical possibilities of BMIs are exciting, there is an important difference between what we *can* build and what we *should* build. That distinction is one that many new technologies confront, and the way that BMI will parse the difference might be similar to how other technologies have done so—especially in genetic engineering and autonomy. But similarities notwithstanding, researchers, operators, and the broader public must think about the implications of developing—or not developing—technologies that interact directly with the brain.

Technically speaking, there are some important hurdles the development community must overcome before this technology can be considered for widespread use or acquisition. First, while BMIs have been demonstrated in multiple applications, we are still far from the sort of fantastic advances we see in Hollywood movies. Take, for example, moving a natural limb, a task that involves hundreds of millions of neurons. Jan's BMI sampled only a few hundred of those neurons. Rather than a natural, almost unconscious movement, using the limb still requires some thought and practice. Such movement is much less difficult than with traditional prostheses but is still limited by the bandwidth of the

BMI. Despite its limitations, today's technology provides us with a glimpse of what might be achievable in the future.

There is also a significant technical issue with the "I" in BMI. To date, the interface has required a surgical implant in the brain. Some individuals may be undeterred by such an invasive procedure, but for many, elective brain surgery is reason enough to walk away. If not, it bears mentioning that the brain is rather inhospitable to foreign objects, limiting the utility of today's devices to several years—not the lifetime that we would want. However, this is a hurdle and not a barrier. Many researchers are working to increase the capability of minimally-invasive BMI technology, and developments look promising. Decades of research and investment in sensing technologies are coming together to bring the possibility of a noninvasive, ball-cap type BMI within the realm of the possible—eliminating today's barriers to widespread use of BMI.

Cost also remains a practical issue. Today, in part because of the necessity of surgery, BMI is expensive—too expensive for widespread application. But there is already evidence that the costs will come down exponentially over time, as they have with many other technical advances.

Money and technology aside, popular perceptions of BMI—and with them the policies and laws that will govern development—are essential to the future of this technology and should be at the top of the "what to think about next" list. We have already witnessed these same conversations related to genetic engineering and autonomous systems. The debate often reveals opposite positions: Either the future will be a technology-enabled utopia or a tragic, science fiction-like dystopia. Because the nuances of the issue are so complicated, we often exaggerate both the negative and positive. At the same time, real answers to public questions about the technology are as difficult for professional ethicists to answer as they are for expert technologists. Take, for example, our work with prosthetics patients. It was a breakthrough, tear-inducing moment when the signal processers for the BMI decoded signals from one of our participants and correctly moved the arm. But put another way, we succeeded in reading a person's mind (albeit crudely at that point). What does that mean for privacy in the future? How could this data affect us in unintended ways? And finally, how should we control access to the data? Likewise, breakthroughs in sensory feedback through BMI have incredible therapeutic potential and could also enable a level of control over machines that would truly be a game changer. But while one person might think of it as enabling human senses, another might see it as putting ideas into someone's head. How can we use this technology to help individuals, while preventing its ability to do them harm?[8] And perhaps most esoteric but still important to our society: does this technology stand to change what it means to be human?

There is no doubt that BMI technology today is having a positive impact by restoring sight and sound, enabling the paralyzed to move, reducing the effects of Parkinson's disease, and offering the promise to treat other neurological conditions. At the same time, BMI could help the nation to address pressing national security concerns. As developers, it is our responsibility to balance these benefits through a sustained dialog between all parties. Many examples show that perceptions about AI are shaped by experiences and exposure. With that in mind, we must be careful to thoughtfully develop the first prototypes and interactions with this technology such that social norms evolve along with the technology and technology is informed by social norms.

As part of this discussion, it is useful to remember what we have learned from Jan, Tim, Johnny, and all those who have participated in similar BMI research projects. It is not about the technology alone but the positive impact BMI can have for all of us, both in improving health and in keeping the nation secure. Jan best reflected this sentiment in a note to the team upon learning that her BMI implants were to be removed:

> And how I am feeling now is this: I've had the time of my life! This is been a fantastic, thrilling, wild ride, and I am so glad I've done this. Being part of this study has enriched my life, given me new friends and coworkers, helped me once again to be a contributing member of society, and taken my breath away. Ever since it began, in my morning prayers, I have thanked God every day for being able to be part of this study. And the rest of my life, I will thank God every day for having been part of this. I have no regrets. . . . I'm sure I will wake up one day in a couple weeks and just sob because I can't go into the lab to work with [the prosthetic limb] anymore. But what I don't think will happen is I will get depressed in the long run. I did this, and no one can ever take that away from me. Long after my name is forgotten, and the names of all the scientists who worked on this project are forgotten, our work will stand and will benefit future generations of paralyzed people and amputees.

BMI is a technology with enormous potential that deserves more attention, resourcing, and development. While it is not generally accessible today, technologists, ethicists, and the public should consider its implications now. SSQ

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Biotechnology

An Era of Hopes and Fears

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Abstract

Biotechnology capabilities continue to increase at a rapid pace. This increase in itself is not unexpected, unforeseen, or inherently good or bad. Increasing knowledge of genetics and cellular function, coupled with increases in computing power, is allowing development of novel, highly targeted treatments for all manners of disease and injury. The potential for breakthrough treatments is higher now than ever before. However, as knowledge and capability increase so does the ability to develop biological weapons with increasing lethality and precision. Every new treatment also represents a potential new weapon.

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In 1996 the world's DNA sequence repository, GenBank, had approximately 5 x 10^8 bases (bits) worth of sequence data in its database.[1] The human genome had yet to be sequenced, and cloning was still a theory. Now the world's genetic databases contain 1.3 x 10^{12} bases of data available for search within seconds.[2] Sequencing is no longer a task for graduate students but is now a commercial service provided by numerous companies offering sequencing and analysis of entire bacterial communities within days. The increase in computing power, combined with the ever growing amount of DNA and protein sequence data, allows deeper insights into the fundamental source of disease. These capabilities are allowing medical providers to identify specific disease characteristics for each individual patient, which allows for increasingly specific and effective treatment plans.

All life on earth is ultimately controlled by each organism's unique genetic code carried in its DNA, and many human disease states can be at-

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tributed to mutations in the chemical structure, and hence information content, of the DNA.[3] For example, noninfectious human disease states, such as cancer or sickle cell anemia, can be attributed to mutations. A mutation may be inherited, or it may arise spontaneously during an organism's lifetime. Any particular mutation may have no effect on a cell, while others can cause a change in cellular function that may increase or decrease the organism's ability to survive in the environment. Today, science has advanced our understanding of genetics and cellular processes to the point where we are developing the ability to identify mutations associated with disease, as well as developing the ability to treat disease by modifying DNA or targeting malformed proteins within a cell. With this information, doctors can design custom treatment plans with increased specificity and likelihood of success.

Researchers can even develop new treatments on a computer. Using molecular modeling software they can design and test existing chemical compounds or even design synthetic molecules capable of modifying the effects of a disease. Personalized DNA sequencing is also becoming a commercial commodity. For example, fitness companies are offering to test your DNA then develop exercise and nutrition plans tailored to your genetic makeup, while other companies offer to identify your genetic ancestry for under $100.[4] Today the cost of DNA sequencing is actually outpacing Moore's law, and to sequence one million bases of DNA literally costs a few pennies.[5]

As we develop our understanding of genetic diseases, we are also developing the ability to attack these diseases at their genetic roots. Again with increased knowledge of DNA sequence information and advances in computers, combined with advances in molecular manipulation of DNA, it is possible to construct certain molecules designed to knock out or modify the expression of a mutated gene.[6] This incredible increase in capability foreshadows the development of immensely effective medical treatments from diseases such as cancer, Alzheimer's, or diabetes and even the ability to edit the genetic errors associated with inherited diseases such as cystic fibrosis or sickle cell anemia.

The scientific understanding of cellular pathways is growing at an incredible pace, and with each advance, there is an opportunity for more potent therapies—and potentially more lethal uses. Unfortunately the ability to heal also opens the ability to harm, and current advances have an inherent ability to be used as biological weapons. Beneficial medical treatments use biotechnology to manipulate cellular function, returning a diseased cell to a nondiseased "normal" state. The application of the same treatment to a healthy cell could result in modifying it to an abnormal state. The enormous capabilities being developed show great promise but have a dark side that cannot be ignored. The idea of advances in biotechnology increasing the biological weapons threat is not new. In 2003 an analysis of gene sequencing and synthesis capabilities found they were following Moore's law of computing power. The analysis also looked at the educational requirements associated with genetic manipulation and found it was no longer exclusive to PhD's but was becoming a global commodity powered by workers holding bachelor's degrees or even certificates of training.[7] In 2006 the National Science Advisory Board for Biosecurity (NSABB) found that commercial synthesis of "small" organic molecules was readily available and routine across the globe.[8] It also found that larger molecule synthesis, and even viral genome construction, was possible but limited to large institutions.[9] This article examines some of the hopes and fears of emerging biotechnology. It is an attempt to survey recent medical advances made possible by advances in biotechnology and at the same time remind the reader that these advances also carry a corresponding threat. Such advances will allow fine tuning of any cellular process associated with disease from cancer to metabolic imbalances but could also become extremely efficient, targeted biological weapons. Because it is not feasible to identify every possible technology or advance, this work focuses on a small sampling of the research published within the past three years.

The Hopes of Biotechnology

Much of the recent research concerns increasing knowledge about the human genome and the proteome, combined with an increasing ability to model and construct custom molecules.[10] This combination is allowing medicine to produce custom therapeutics designed to cure disease by modulating cellular action at the molecular level. The most-helpful, rapidly emerging biotechnologies highlighted here include computer modeling and genomic modification.

Computer Modeling and Analysis and Synthetic Drug Design

There are numerous ways to artificially interfere with the actions of proteins and cause a change in a cell's behavior.[11] For example, any process that changes the shape of a protein can have an impact on cellular function. As knowledge regarding the fundamental structure of proteins grows, researchers are increasingly able to apply that knowledge to engineer novel molecules (drugs) designed to modify the protein's activity, hence affecting cellular function and "curing" the patient of the associated disease condition. However, these advances in biotechnology are tied to advances in computer modeling capability, which is allowing greater understanding of protein activity within the cell.

While the idea of altering cellular communication using engineered molecules appears straightforward, it requires significant computational capabilities. The ability to visualize a protein and predict its actions requires information on its fundamental sequence (DNA and/or amino acid) coupled with the computing power to calculate the thousands of molecular interactions that drive the three-dimensional shape (and hence functionality) assumed by the protein. The model must then predict the multitude of chemical interactions among the protein of interest and other notional molecules with therapeutic potential. Today we have reached a point in sequence data and computer power where it is possible to model complex proteins and even protein/drug interactions without an actual laboratory.

Pharmacophore modeling is a process where a molecule is modeled in three dimensions. The model allows researchers to screen other molecules and select those that demonstrate (in the computer) the ability to interact with the target molecule. This allows a relatively quick and cost-effective method to screen hundreds to thousands of compounds without requiring individual cell cultures for each screen. By combining different models and programs, researchers are able to screen thousands of compounds and ultimately predict the molecular interactions of candidate molecules down to amino acid position, type of bonds, and even molecular distances.

This ability to model molecular structures and chemical interactions is fundamental to the idea of rational drug design, where researchers can create molecules designed for specific molecular interactions. This idea is not new, but its effectiveness has been limited by protein data and modeling capability. Today, computer models have improved to a point where researchers are not only able to screen existing compounds for potential interactions but can also use models to reverse engineer synthetic molecules (drugs) designed to interact in specific ways with the target molecule.[12] The ultimate goal is to perfect modeling of therapeutic molecules to a state where "treatments are custom-designed and based upon the molecular genetic profile of normal versus cancerous tissues in patients."[13] In other words, each individual cancer patient will be screened and have a custom treatment optimized to match the genetic characteristics of their particular tumor.

Modeling capabilities can therefore be used to quickly identify the most likely candidates for drug development. Researchers can also use these models to examine how different molecules interact with the target, pulling out the most important molecular positions and orientations. This knowledge can then be used as the basis for the rational design of synthetic compounds with an optimal configuration to bind the target of interest. For example, researchers investigating cancer therapies based upon proteins that help maintain DNA structure were able to screen over two million compounds and identify four compounds with significant binding capability and potential utility as anticancer drugs.[14] Additional examples of current medical trials of compounds designed by pharmacophore modeling include compounds designed as modulators of cardiac action,[15] acetylcholinesterase inhibitors for treating Alzheimer's,[16] cell checkpoint modulators for cancer,[17] and enzyme blockers to treat Chagas disease.[18]

In addition to developing novel therapeutics, greater understanding of genetics and proteomics is uncovering previously unknown cellular communication pathways that can then be modulated to increase healing. For example, identification of existing genetic/cellular pathways previously unassociated with disk disease has identified many signal-modulating proteins as novel emerging treatments for disk degeneration.[19] The increased knowledge in signaling pathways is being directly translated into medical treatments, where signaling proteins or genes are being harnessed to construct cell-instructive biomaterials. These are synthetic materials supplemented with molecules known to enhance healing and regeneration within the graft or scaffold (for bone and tendon repair). The supplemental molecules mimic natural regenerative signals, controlling processes necessary for healing such as cellular adhesion, differentiation of cells, and growth of new blood vessels.[20] These pathways can be modeled for each individual tissue type, and this knowledge is being used to fine tune the administration of growth factors and even to genetically modify stem cells that are injected into injury sites to control and enhance the repair process.[21]

Genomic Modification

The dream of genetic therapy—fixing genetic-based diseases by changing an individual's DNA sequence to reverse harmful mutations—has been around for many years. In theory, genetic modification is straightforward, but in practice, it requires an in-depth understanding of the organisms, normal versus mutated genetic sequence, the ability to predict which changes need to be introduced into the DNA to produce the desired result, and an ability to affect those changes without destroying the organism.

Twenty years ago, the total content of the human genome was unknown. To sequence the human genome, the US government funded the Human Genome Project, a groundbreaking program to read the approximately three billion bases of DNA contained in the human genome. The project ran for 13 years (1990–2003), with a total expenditure of $3 billion—which supported many biotechnology advances in addition to directly sequencing the human genome.[22] Today, sequencing capabilities have advanced to the point where commercial companies offer to completely sequence a human genome sample (with 30x coverage) for approximately $1,500 in about two weeks' time.[23] Armed with this vast amount of sequence data and an incredible increase in the ability to manipulate DNA, researchers are able to glean information about disease at the DNA and protein levels. Sequencing and computer analysis can also help researchers better understand the cellular and genetic processes that underlay "traditional" or even "ancient" homeopathic treatments. This knowledge then allows scientists to refine and tailor existing drug regimens.[24] Several different techniques for modifying DNA for medical purposes have advanced to the point where they are being tested on humans in clinical environments or approved as drugs. These include virus manipulation, genome editing, noncoding DNA, and epigenetics.

Viral Manipulation

Viruses are infectious particles that use host cells to replicate, and the idea of harnessing viruses as a mechanism to deliver engineered DNA into a host cell is quite common. Viruses replicate by injecting their genetic material into a host cell, which then hijacks the host cell into producing progeny virus particles, and often target only specific subsets of cell types within an organism. While viruses present researchers a natural way to deliver therapeutic DNA, the need to understand the genetic code and an ability to precisely manipulate viral genetic material has historically worked against this approach. Today, as knowledge and techniques advance, the ability to use a virus to alter a target cell's DNA as a mechanism to combat disease at the genetic level is becoming a reality. A review of treatments for arthritis alone lists nine different examples of virus-based gene therapy being used to modulate inflammation.[25] Viral- and nonviral-delivery gene therapy are also being investigated for disk restoration, tendon repair, and bone repair.[26]

Another advance in the manipulation of viral genetics is the increasing use of chimeras—novel viruses constructed from the genetic material of at least two different "parent" viruses. In theory, it is possible to create novel viruses that combine desired traits from both parents. The idea of viral chimeras is not new and was pursued by the Soviet biological weapons program in an attempt to enhance the effectiveness of their weapons.[27] While it is unknown if the Soviets succeeded, viral chimeras are commonly used today as research tools. For example, researchers investigating the immune system may take a known disease-causing virus and modify it by adding novel genes from another virus that affects the host's immune system. They will then infect an animal with this chimeric virus to gain an understanding of how the immune system works.[28] One such experiment—which caused extreme concern in the biodefense community—was a mouse pox virus modified with genes to modulate the mouse immune system. When tested in the laboratory, the modified virus killed almost every infected mouse, including previously vaccinated mice and strains bred to be disease resistant.[29] The ability to manipulate the immune system is an important tool for researchers and offers potential for medical treatments but could have extreme implications if used to enhance the lethality of a biological agent.

While viral chimeras are a routine tool in laboratory practice, they are becoming common in therapeutic roles, for instance in vaccine production. A live, nonattenuated vaccine constructed from Eastern equine encephalitis (EEE) virus and Sindbis virus has demonstrated the ability to protect primates from EEE.[30] A small sample of some other chimeric vaccines include Rift Valley fever/Moloney murine leukemia virus tested in mice,[31] a Japanese encephalitis/yellow fever vaccine virus in use in humans,[32] and a multistrain human papillomavirus has been tested in mice.[33] While viruses serve as one mechanism to modify the genetic code, the process suffers from many biological obstacles that are beyond the scope of this review.

Genome Editing

Genome editing refers to the ability to directly modify the DNA sequence of an organism without relying upon an intermediate mechanism, for example a virus or radiation, to induce genetic changes. With adequate sequence knowledge and the appropriate molecular tools, one could—in theory—modify any section of DNA. It would be possible to turn a gene off, turn a gene on, or alter the expression patterns or product of a particular gene. While several editing techniques have been available in the past, they were relatively inefficient and required a relatively high level of sophistication to employ.

Recently a revolutionary genetic editing tool referred to as CRISPR/Cas9 has been developed and commercialized.[34] This tool is so powerful it was specifically identified by retired USAF Lt Gen James R. Clapper, director of national intelligence, as a potential bioterrorism threat.[35] This molecular system allows researchers to design an experiment in which they can modify any region of DNA essentially at will. The technique has been perfected and commercialized to the point where reaction kits are available online for hundreds to thousands of dollars. A simple library database search for "CRISPR"—limited to the last two years—returned over 2,000 journal articles, which is a rate of almost three per day. Just a few examples of human CRISPR-related research areas include beta-thalassemia, retinal cell regeneration, generation of human organs from pigs, and generation of entire knockout libraries of the human genome. Chinese researchers have used this technique to increase muscle mass and hair production in dogs and goats and alter the neurological development in monkeys. They have even attempted to correct the genetic mutation responsible for beta-thalassemia in human embryos, although all attempts so far have failed.[36] This technique is moving into the commercial space as well. In 2015 Bayer HealthCare Pharmaceuticals announced a joint venture with CRISPR Therapeutics to "discover, develop and commercialize new breakthrough therapeutics to cure blood disorders, blindness, and congenital heart disease."[37]

In addition to the potential to modify genes at will, the CRISPR also holds the potential to allow researchers to develop a "gene drive" system, where traditional Mendelian inheritance and Darwinian survival no longer dictate the prevalence of a gene within a population. Under normal conditions, the prevalence of a gene through a population is controlled by the number of parents with that gene in the population and the statistical likelihood that their offspring will inherit that gene (Mendelian inheritance). The spread of a mutation is also influenced by its contribution to the fitness of an individual; genes that cause disease or disadvantage will not spread rapidly, if at all, through a population, while those genes that offer an advantage will be more likely to spread (Darwinian survival).

Using CRISPR, researchers are able to construct mutations that drive the gene through a population much more rapid than predicted by Mendelian genetics and do so with no regard for the increase or decrease in fitness associated with the mutation. These drives offer the potential to insert and drive a mutation into a population within a few generations—even if detrimental to the offspring. A drive could be of great benefit if used to insert a beneficial trait quickly to a native population of insects or plants. Conversely, a drive could be used to weaken or even lead a population to extinction.[38] The use of genetic modification and drives to control insect populations is being commercialized by at least one company, which has proposed the use of genetically modified mosquitoes to control the current Zika virus outbreak.[39]

"Dark" or Noncoding DNA

As science learns more about the genetic code and its physical structure, the simple DNA → RNA → protein model for information flow becomes more complex.[40] It is known that the vast majority of the human genome does not contain sequences that directly result in proteins. Years ago, this noncoding DNA was seen as "junk" or evolutionary baggage that may or may not serve any practical purpose. As sequencing and computer analysis advance, researchers are identifying significant regions of DNA previously regarded as junk that demonstrate the ability to impact cellular function without coding for a functional protein, as would a traditional gene. Two examples of nonprotein-directed control over DNA expression are noncoding RNA and physical alteration of the higher order structure of the DNA molecule itself.

Traditional thinking held that an RNA molecule needed to be translated into a protein in order to influence cellular function through the subsequent action of the protein, which has been found to be false. MicroRNAs (miRNA) are a class of RNA molecules that do not code for proteins but instead are produced for the express purpose of interfering with other message-carrying miRNA molecules, hence stopping protein production. MicroRNAs are believed to play a role in functions such as controlling tissue development or maintaining homeostasis.[41] Imbalances in miRNA expression have been implicated in diseases such as cancer, fatty acid metabolism, glucose metabolism, and pancreatic function and have been implicated in viral pathogenesis.[42] Therefore, it is not surprising that pharmacy and academia have explored the potential use of miRNAs to treat disease, for example developing miRNAs to target components of the inflammatory response implicated in arthritis.[43]

A fundamental understanding of the genetic component of disease also gives researchers the ability to mimic miRNA's behavior through the employment of antisense treatments. An antisense treatment or drug is a synthetically designed and constructed oligonucleotide—a short section of DNA or RNA, often single stranded—that has a genetic sequence capable of binding a cell's genetic material and interfering with the normal flow of genetic information. An antisense code is the negative image of the normal information contained within the cell. It can be used to block the message being produced by the cell, in essence 1 (sense) + (-1) (antisense) = 0 (no signal). To successfully develop an antisense treatment, two requirements exist: "silencing of specific genes in a defined population of cells which will produce therapeutic benefits" and "surface receptors expressed specifically on the cell population of interest that can deliver RNA ligands intracellularly."[44] In other words, one must know the specific gene or signal to target and have the ability to deliver the therapeutic molecule to the specific cells responsible for the disease.

Epigenetics

Epigenetics is another area of genetic regulation where gene expression is controlled by factors outside of the core DNA → RNA → protein construct. Specifically, epigenetics refers to the idea that factors external to the actual information contained within the gene sequence also affect the physical appearance of an individual. An example of this phenomenon is the role the three-dimensional structure of DNA molecules play in genetic expression. Genes can be turned on or off based on changing the shape of the DNA molecule, regardless of the fundamental genetic sequence. In this case, a gene turned off by an epigenetic modification will not have a chance to influence the cell by producing a protein.[45] An understanding of epigenetic factors could allow researchers and therapists to selectively turn on or off copies of genes within an individual's genome by modifying the structure of the DNA molecule versus changing the genetic sequence as would be done in genetic engineering. A recent review of epigenetic research on cancer examined studies in which researchers have been able to modify the DNA structure to either alter cellular development or reprogram cancer cells (on or off). The review identified 17 significant studies during the last 10 years in which researchers developed the ability to reprogram cancer cells and judged that six of the techniques had commercial therapeutic potential.[46]

Epigenetic studies are also revealing that DNA has different characteristics within distinct human populations. One difference is DNA methylation, wherein the DNA molecule is chemically modified at specific sites. Methylation can turn off gene expression and is thought to be one mechanism used by the body to regulate the ability of different tissues to express different genes.[47] Methylation patterns can be inherited but also show changes within organisms as they transition through different phases of development and aging.[48] There is also evidence that methylation patterns differ within populations. A recent study comparing male versus female DNA found a significant difference in the methylation pattern between male and female genomes. The study found 1,184 regions with stable methylation differences and argues that "the differences between men and women are so substantial that they should be considered in design and analysis of future studies."[49] Other research has demonstrated that the methylation patterns of cancer-associated genes differ between ethnic populations.[50] Knowledge of unique methylation patterns may be used to enhance a particular treatment but, in theory, could also be used to design weapons that target individuals with specific methylation patterns, leaving other parts of the population untouched.

The Future of Biotechnology and Medicine

As shown by these few examples, the worlds of genetics, proteomics, and medicine are converging—aided by advances in computing power. This convergence has allowed researchers to dig deeper into the fundamental causes of disease states. The deeper we dig and the more we understand, the more we are able to develop treatments with increasingly narrow focus and much greater effective action. This has allowed us to go from chance observations of mold growth on a petri dish killing bacteria (penicillin) to systematic and deliberate design of compounds targeted against specific molecular links in the disease process. Analogously, medicine is moving from World War II's firebombing of entire cities toward today's GPS/laser-guided weapons that hit within feet of the target. We are developing the ability to cure disease by reaching into the genome or proteome and modifying single DNA bases or blocking specific molecular bonds, giving modern medicine unprecedented ability to restore healthy processes within the cell.

These advances give hope for a new era of medicine in which cellular imbalances can be treated and genetic disorders can be fixed at the tissue or even embryonic stage. Instead of using insulin injections to manage diabetes, it is possible to envision the ability to infect pancreatic cells with a virus that alters the genome of those cells, restoring normal insulin production. It may be possible to use custom-designed genes delivered to specific cells through an artificially constructed virus to regrow nerve tissue after spinal cord trauma or program the heart to regrow muscle tissue lost to a heart attack. In the future, every individual's cancer risk could be assessed at birth by screening for cancer-associated genetic mutations. Based upon that assessment, patients could be periodically monitored for abnormal levels of cancer-associated proteins. Those at risk will then be treated to downregulate the expression of risk-associated proteins, preventing cells from becoming cancerous. With our increased understanding of the differences within our DNA, these treatments might be further optimized to reflect methylation patterns based upon gender and even ethnicity. As these advances become routine medical practice, they will represent a new era of medicine dependent as much on modeling and synthesis as trial and observation.

The Fears of Biotechnology

With any scientific advance, there is always the possibility it will be used for harm. Historically, biological weapons have been developed by harnessing naturally occurring pathogens that were especially good at infecting humans and causing disease. The task of the early bioweaponeers was to take these natural agents and turn them into weapons by improving characteristics such as virulence, survivability, and ease of dissemination. Techniques that use genetic manipulation to increase virulence or convey antibiotic resistance have been evolving for decades but have been comparatively slow and labor intensive. Today's advanced techniques, such as CRISPR, will give bioweaponeers almost unlimited ability to modify any virus, bacteria, protein, prion, or parasite with any trait they desire. While there is no guarantee any singe modification would produce a viable "super" agent, the cost and time investments required to conduct a modification are low enough that many different combinations could be attempted with relative ease.

It is also important to remember that plants and animals can also be targets of biological weapons. The massive financial impact associated with natural diseases outbreaks such as foot-and-mouth or bird flu makes agriculture a serious target for an adversary seeking to inflict financial damage while not directly harming human life. This threat must be viewed with the realization that wholesale genetic modification of viable animals is already being performed in laboratories around the world and is being commercialized. The idea of genetic control over disease-vector insects could save millions from diseases such as dengue and malaria. However, what would be the impact of intentionally crashing the bee population, removing a predator from the ecosystem, or making a crop parasite resistant to insecticides?

Fortunately, most of the technologies discussed in this article remain experimental and require extremely sophisticated laboratories. Effective weaponization and large-scale employment of these new capabilities as a weapon would require a dedicated effort by a state sponsor. It is one thing for a medical provider to inject an experimental therapy into a patient but a much more difficult matter to deliver that substance simultaneously to thousands of people in a diverse environment. Traditionally, biological weapons require the agent be ingested, inhaled, or injected into the target—not trivial problems, and ones the US and Soviet programs spent many years and funds to overcome. Therefore, it is unlikely they present a near-term threat.

However, there is no reason to believe this will always be the case. Genetic techniques that took a 1990s-era graduate student months to master and days to accomplish are now sold as ready-made kits that perform the same process in hours. The commercialization of biotechnology consistently moves today's high-end techniques from sophisticated laboratories to common commercial kits.

As technology evolves—becoming accessible, cheaper, and easier to use—what are the associated threats? Compare the "cutting-edge" technology from 15 years ago—in flip phones, low-definition televisions, and dial-up modems for internet access—with the capabilities available today in a common smartphone, which offers high-definition, wireless internet access from almost any location in the country. The spectacular advances in biotechnology are no less amazing. Now think of the same rate of technological advance 5, 10, or 15 years in the future, and consider some hypothetical scenarios where today's cutting-edge, emerging biotechnologies are now commonplace and are used to produce biological weapons.[51]

One such scenario involves a "garage biologist," lone-wolf terrorist who seeks to create a "stealth" biological weapon to evade detection or medical treatment.[52] Many biological detection systems are based upon antibody recognition. These systems are able to "look" for unique molecules present on the surface of biological agents. To be effective, detection systems must look for markers present on the agent of concern and not present on other nonhazardous background bacteria. In an almost identical process, the body looks for molecular markers on invading organisms and targets them for destruction. Vaccines present the body's immune system with inert "training" targets that teach the body how to identify and eliminate invading organisms.

Both systems rely upon the ability to discern specific molecular patterns to identify bacteria or viruses. However, as has already been discussed, the nature of the surface molecules is related to the genetic information of the organism. An adversary who is aware of our detection techniques or our vaccine components could alter the surface molecules of a threat agent, rendering the detection or protective capability ineffective. To do this, an adversary could model the molecular interactions between the surface molecule on the threat agent and the detection molecule used by the sensor. Once the reaction is understood, the adversary could model modifications to the agent's surface markers that would negate the recognition reaction. The changes in the surface molecule could then be reverse engineered to the source DNA sequence, which could be modified by a CRISPR-based replacement with a new sequence and resulting surface marker. Successful modification of a pathogen in this manner would essentially make it a "new" threat organism and would require the defensive community to develop new vaccines or new detection capabilities that could take months or years to implement.[53]

Another relatively easy scenario to envision is the development of a new and extremely fast-acting biological toxin. Traditional biological toxins rely upon molecules produced by other organisms that happen to be hazardous to humans. For example the toxin ricin is found in castor beans, and the botulinum toxin is produced by a bacteria. Countries seeking to weaponize these agents simply adapted what nature developed, resulting in a weaponized form capable of mass dissemination and entry into the target. As the agents were from nature, their relative toxicity and method of action were essentially "constants" within which the weaponeers had to work. Improvements in toxicity could come from scouring nature for more toxic versions of the same organism, or the organisms could be mutated in the lab, which was generally a haphazard and time-consuming process.

Emerging biotechnology and computing capabilities will remove the need to scour nature for toxins and will allow weaponeers to custom design their own toxins. The idea of pharmacophore modeling of drugs has already been discussed. One of the uses for this technology was to model the molecules responsible for cardiac polarization.[14] Polarization and depolarization of cells is a critical process utilized by nerve and muscle tissue to convey electrical signals. The polarization process relies upon molecular signals and receptors that open and close gates in the cell's membrane, allowing a change in the electrical potential. As the ability to model the receptors increases, it becomes possible to design, through computer simulation, molecules that will target and inactivate these receptors—hence, shutting the gates and preventing the electrical signal. Assuming an acceptable delivery system, a weaponized form of this type of molecule could shut down a victim's entire nervous system (brain) or muscular system (heart), causing rapid death with little chance of successful medical intervention.

In a more complex scenario using gene silencing techniques similar to those used in cancer treatments, it could be possible to design a RNA-based weapon capable of killing a specific tissue. It is possible to imagine a silencing system that is designed to target and kill only kidney cells. One possible delivery mechanism for such a device would be inserting the silencing genetic code within a viral chimera. A weaponeer could take a highly infectious but nonlethal virus—such as the common cold—and modify it to contain the silencing system. Upon infection, the silencing genes could be triggered and result in the death of the target tissue. Depending upon the dose, effects could range from a minor to total loss of kidney function. Victims would be dependent upon dialysis for survival, causing a massive strain on medical infrastructure and budgets. As science continues to refine the human genome and focuses on identifying the genes and proteins associated with tissue expression, the list of potential targets grows and is available to anyone with an internet connection.

A final scenario is the ability to eliminate a population from nature using the CRISPR-Cas9 system to construct a gene drive. Such a drive system is a reality and is currently in use to control mosquito populations.[54] Introducing a gene drive into a population eliminates the statistical and evolutionary factors used by nature to control the prevalence of mutations within a population. While current gene-drive systems are tightly controlled and designed to prevent spread in nature, a malicious gene-drive system could be used to eliminate an animal population from a large geographic region.

The idea of selective breeding predates knowledge of genetics, starting when the first farmers selectively bred plants or animals with the "best" traits to increase yield. Weak or disease-prone stocks were conversely not selected and reduced from the population. Today's scientists use knowledge of genetics to achieve the same goals as the early farmers. Traits such as size and disease resistance are, at their core, dependent upon the genetic makeup of the organism and hence can be manipulated in the laboratory. Honeybee hive collapse is a real problem in North America and the subject of ongoing research, seeking to discover the cause and at the same time identify genetic traits that convey resistance to the phenomenon.[55] It stands to reason that while some genetic traits will convey increased resistance, other traits will make the bees more susceptible to a particular condition. Instead of looking for a cure, a malicious research program would focus on identifying genetic traits associated with the most-susceptible populations.

Once identified, a susceptibility gene could be incorporated into a gene-drive system, ensuring that close to 100 percent of the offspring from the engineered bees will carry the susceptibility gene. In this scenario, a large number of engineered bees could be raised in a protected environment; then a large population of engineered drones would be released to outbreed the natural population. Once introduced into the population, the hives in the area would become increasingly susceptible to collapse. The collapse of the bee population in an agriculturally intense geographic area could have enormous secondary effects, as crops that rely upon pollination would crash along with the bee population.

These are only a few hypothetical examples that, while they can be imagined, still require significant effort and resources to actualize. However as scientists continue to develop their understanding of cellular function, one can imagine an ability to interfere with any genetic or chemical reaction responsible for cellular function, essentially making any tissue or cell a potential target for a biological based weapon.

Epilogue

The goal of this work is to inform the defense community of the evolving power of biotechnology in the hope the United States will remain vigilant with its biodefense program. There is no easy answer to the dilemma of the hope and fear in biotechnology. Advances in biotechnology rapidly outpace the ability of governments to regulate. This work is often performed by commercial companies and not necessarily reliant upon government funding. It is also interesting to note that a retroactive review of journals cited in this article reveals less than 50 percent were written within the United States. While regulation or legislation may address some issues, it clearly cannot control the direction and pace of this research.

As a nation and as a military the United States tries to align its defensive programs to account for future threats. However, we have yet to develop a full line of defenses against biological weapons developed during the Cold War. US efforts to deal with flare-ups of diseases such as Ebola highlight our partial successes but also show how resource-intensive and time-consuming it can be to respond to even a known and somewhat expected threat. The issue is not unique to the United States, as the whole world is facing these issues. The international community has yet to develop an effective enforcement mechanism for the Biological Weapons Convention. The physical detection of biological weapons programs remains extremely difficult, while covert offensive programs have been conducted under the cover of overt defensive or medical programs. In many ways, the world relies upon behavioral norms and moral behavior as much as any other mechanism to prevent a biological attack.

Will these restraints continue in the future, and if not, what can be done about it? The ability to imagine the biotechnology and medical capacities that will be available 10–15 years in the future is often limited by what we experience today. Likewise, it is impossible to predict how "low" today's cutting-edge biological techniques will be pushed by commercialization of laboratory practices. However, it is safe to say that the technology and knowledge will spread worldwide, and it will not be possible for the United States to exert total control over the process.

There is no magic bullet or novel approach for how to keep up with a rapidly evolving biological capability that is only one of many potential threats facing the nation. While "nimble" or "adaptive" responses may be cliché, they are needed and must be fed by the current threat assessment. What we cannot do is assume that these technologies will always be used for good; a strong sense of pessimism or red-team analysis must be practiced if we hope to anticipate the next biological threat before it is employed. SSQ

Notes

1. National Center for Biotechnology Information, "GenBank Release Notes," US National Library of Medicine web site, accessed 28 December 2015, http://www.ncbi.nlm.nih.gov/genbank/statistics.

2. Ibid.

3. DNA is a nucleic acid, a molecule made of pairs of chemical bases (adenosine, thymine, cytosine, and guanine) arranged in sequences that contain information, much in the way a computer code consists of ordered ones or zeroes. In this manner, each base could be thought of as one "bit" of information in a computer code. The cell converts the information within the DNA into another nucleic acid, RNA, in a process called *transcription*. The RNA is used by the cell as a blueprint to build proteins in a process called *translation*. RNA used to produce proteins is called messenger or mRNA. Not all RNA produced in the cell is mRNA, and RNA serves many other biological functions.

Proteins are constructed by creating a string of molecules known as amino acids. The sequence of amino acids is determined by the DNA → RNA sequence used as the blueprint to assemble the amino acids. There are 20 different amino acids that can be used at any one position. The chemical properties of the amino acids and their relative sequence dictate how the string of amino acids will fold to create a unique shape that directly influences the protein's characteristics. Proteins are the most visible physical manifestation of one's genetic makeup—for example, blue or brown eyes, A- or B-type blood, and so forth. Proteins also perform a variety of less-visible biological functions, such as providing structure, moderating chemical reactions, sending and receiving signals, and moderating cellular growth patterns.

A *mutation* is a change in the information contained within the DNA. The change in information may change the production of a cellular product or mechanism. In and of themselves, mutations are neutral; the environment determines if the mutation is detrimental to the organism, beneficial to the organism, or is neutral toward the fitness of the organism.

4. Steven Moore, "Genetics Company Looking at What Can Make Athletes Better," *Las Vegas Review-Journal*, 14 November 2015; and "Discover the Family Story Your DNA Can Tell," Ancestry.com (web site), http://dna.ancestry.com/?s_kwcid=ancestry+dna&gclid=CLOhnOC43soCFceQHwodTC0GxQ&o_xid=58712&o_lid=58712&o_sch=Paid+Search+%e2%80%93+Brand.

5. Kris Wetterstrand, "DNA Sequencing Costs: Data from the NHGRI [National Human Genome Research Institute] Genome Sequencing Program," Large-Scale Genome Sequencing and Analysis Centers web site, 24 May 2016, http://www.genome.gov/sequencingcosts/.

6. This is most often accomplished by using oligonucleotides—short nucleic acid polymers used in research, genetic testing, and forensics. Oligonucleotides are usually comprised of 13 to 25 nucleotides and are designed to hybridize specifically to DNA or RNA sequences. By binding, they can block or modify the expression of the gene.

7. Robert Carlson, "The Pace and Proliferation of Biological Technologies," *Biosecurity and Bioterrorism* 1, no. 3 (2003): 203–14.

8. A reoccurring theme in the development of biotechnology is the ability to recreate biological process in the laboratory. Many original bioengineering techniques required researchers to harness bacteria and viruses to synthesize or modify molecules. As biotechnology advances, the technology to make DNA, RNA, and proteins from their raw materials using laboratory machines is available and common in all modern laboratories.

9. National Science Advisory Board for Biosecurity, *Addressing Biosecurity Concerns Related to the Synthesis of Select Agents* (Washington, DC: National Institutes of Health, December 2006), http://osp.od.nih.gov/sites/default/files/resources/Final_NSABB_Report_on_Synthetic_Genomics.pdf.

10. The term *genome* refers to the entire genetic component of a particular organism. While nearly every cell contains a complete genome, it only expresses a portion of the genome in the form of proteins. The protein content of a particular cell at a particular time is referred to as the *proteome*. The proteome varies from cell to cell, depending upon function, and can vary within cells over time as the cell responds to external stimuli.

11. Cellular actions, especially in complex organisms, are controlled by complex intracellular communication systems that rely heavily on proteins to function correctly. As with any communication system, for the system to function properly there must be a correct signal or message, plus it must be transmitted correctly, it must have a receiver, and it must be understood. In the case of a cell, a signaling protein is generated from the genetic code in the DNA then (in this example) secreted into the blood. It must then find only the intended target cells, which must recognize the presence of the signal protein and then alter their activity in the correct pattern. In many cases, the interaction between signaling proteins and target cells is mediated by receptors located on the surface of the target cell. The signal and receptor molecules interact through a combination of shape and charge recognition. Mutations in the

DNA can affect the shape of the signal or receptor molecules, altering the flow of information. It is possible to imagine a receptor that, through a mutation, becomes "blind" to the signal or, on the opposite extreme, the receptor behaves as if the signal is always present. In the first case, the target cell will never respond; in the second case, the target cell will be in the response state 100 percent of the time. It is also possible to introduce a third molecule (a drug) that can interact with the signal or receptor molecule, changing the flow of information and cellular action.

12. Radoslav Krivák and David Hoksza, "Improving Protein–Ligand Binding Site Prediction Accuracy by Classification of Inner Pocket Points Using Local Features," *Journal of Cheminformatics* 7, no. 1 (December 2015), 12; and Sheng-Yong Yang, "Pharmacophore Modeling and Applications in Drug Discovery: Challenges and Recent Advances," *Drug Discovery Today* 15, no. 11–12 (June 2010): 444–50.

13. Nirmal K. Prasad, Vishnupriya Kanakaveti, Siddhartha Eadlapalli, Ramakrishna Vadde, Angamba Potshangbam Meetei, and Vaibhav Vindal, "Ligand-Based Pharmacophore Modeling and Virtual Screening of RAD9 Inhibitors," *Journal of Chemistry* 2013, no. 15 (2013): 1–7.

14. Ibid.

15. Yuko Yamakawa, Kazuharu Furutani, Atsushi Inanobe, Yuko Ohno, and Yoshihisa Kurachi, "Pharmacophore Modeling for hERG Channel Facilitation," *Biochemical and Biophysical Research Communications* 418, no. 1 (February 2012): 161–66.

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17. Prasad et al., "Ligand-Based Pharmacophore Modeling."

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20. Christine A. Cezar and David J. Mooney, "Biomaterial-based Delivery for Skeletal Muscle Repair," *Advanced Drug Delivery Reviews* 84 (April 2015): 188–97; Marc A. Fernandez-Yague, Sunny Akogwu Abbah, Laoise McNamara, Dimitrios I. Zeugolis, Abhay Pandit, Manus J. Biggs, "Biomimetic Approaches in Bone Tissue Engineering: Integrating Biological and Physicomechanical Strategies," *Advanced Drug Delivery Reviews* 84 (April 2015): 1–29; and J. Leijten, Y. C. Chai, I. Papantoniou, L. Geris, J. Schrooten, and F. P. Luyten, "Cell Based Advanced Therapeutic Medicinal Products for Bone Repair: Keep It Simple?," *Advanced Drug Delivery Reviews* 84 (April 2015): 30–44.

21. Martin J. Stoddart, Jennifer Bara, and Mauro Alini, "Cells and Secretome—Towards Endogenous Cell Re-activation for Cartilage Repair," *Advanced Drug Delivery Reviews* 84 (April 2015): 135–45.

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23. "NGXBio Next Generation Sequencing Price Quote," 2016, accessed 28 January 2016, https://ngxbio.com/quote.php#getQuote/results.

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27. Ken Alibek and Stephen Handelman, *Biohazard: The Chilling True Story of the Largest Covert Biological Weapons Program in the World, Told from the Inside by the Man Who Ran It* (New York: Random House, 1999).

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32. Kamal Desai, L. Coudeville, and F. Bailleux, "Modelling the Long-term Persistence of Neutralizing Antibody in Adults after one Dose of Live Attenuated Japanese Encephalitis Chimeric Virus Vaccine," *Vaccine* 30, no. 15 (March 2012): 2510–15.

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34. Clustered regularly interspaced short palindromic repeats (CRISPR, pronounced crisper) are segments of prokaryotic DNA containing short repetitions of base sequences. The CRISPR/Cas9 system is a prokaryotic "immune system" in that it is a genetic/protein combination which is able to "remember" previous viral infections and then cut specific sections of viral DNA, preventing successful infection of the bacteria. The bacteria does this by incorporating short, specific sections of the viral DNA into its own DNA. This DNA sequence then serves as a reference to guide the molecular complex to recognize invading viral genomic material.

When recognized, the complex guides the Cas9 protein to the specific DNA sequence, which is subsequently cut into smaller sections, destroying the virus. Scientists have been able to harness this complex and by reprograming the guide sequence with any desired sequence. In this way laboratories are able to design molecular "scissors" that can be used to cut and modify any sequence of DNA with extreme precision. For an in-depth review see Rodolphe Barrangou, "The Roles of CRISPR-Cas Systems in Adaptive Immunity and Beyond," *Current Opinion in Immunology* 32 (January 2015): 36–41.

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37. Mike Orcutt, "Big Pharma Doubles Down on CRISPR for New Drugs," *MIT Technology Review*, 13 January 2016, accessed 22 January 2016, http://www.technologyreview .com/news/545366/big-pharma-doubles-down-on-crispr-for-new-drugs.

38. Kevin M. Esvelt, Andrea L. Smidler, Flaminia Catteruccia, and George M. Church, "Concerning RNA-guided Gene Drives for the Alteration of Wild Populations," *eLife* 3 (July 2014), https://elifesciences.org/content/3/e03401.

39. Alanna Petroff, "Fighting the Zika Virus with Mutant Mosquitoes," *CNN Money*, 28 January 2016, http://money.cnn.com/2016/01/27/news/companies/zika-virus-oxitec-mos quito-brazil/index.html.

40. The central dogma of genetics is that information flows from DNA, is transcribed to RNA, and then is translated to proteins. The expressed proteins are then associated with physical traits (eye color) or metabolic processes (digestive enzymes). Interruption of the information flow at any point in this process can affect the overall physical nature of the organism. It is generally thought that this mechanism was the primary, and even only, mechanism for influencing the appearance and function of an organism. The identification of DNA sequences that were turned into RNA for the express purpose of modifying expression of a different genetic pathway significantly altered this view.

41. *Homeostasis* is the ability of a cell or organism to maintain a stable internal environment. This includes variables such as temperature, salt levels, pH, sugar content, and so forth. The inability of a cell or organism to maintain homeostasis will result in incorrect behavior or even death.

42. Scott M. Hammond, "An Overview of MicroRNAs," *Advanced Drug Delivery Reviews* 87 (June 2015): 3–14.

43. Venkatesha et al., "Cytokine-Modulating Strategies."

44. James O. McNamara, Eran R. Andrechek, Yong Wang, Kristi D. Viles, Rachel E. Rempel, Eli Gilboa, Bruce A. Sullenger, and Paloma H. Giangrande, "Cell Type–specific Delivery of siRNAs With Aptamer-siRNA Chimeras," *Nature Biotechnology* 24, no. 8 (August 2006): 1005–15.

45. An example of epigenetic modification and expression of appearance is a calico cat. In mammals, the female has two X chromosomes but only uses one to produce proteins. Early in embryonic development one X chromosome in each cell is shut down by tightly winding it, preventing gene expression and creating what is known as a Barr Body. This is a random process. The patches in coat color associated with a calico cat (which can only be female) are the expression of the coat color genes associated with the two different X chromosomes, only one of which can be expressed by any one cell.

46. Açelya Yilmazer, Irene de Lázaro, and Hadiseh Taheri, "Reprogramming Cancer Cells: A Novel Approach for Cancer Therapy or a Tool for Disease-modeling?," *Cancer Letters* 369, no. 1 (December 2015): 1–8.

47. As every cell in an organism contains the same DNA blueprint, it is essential that as the organism develops from a fertilized egg to a fully functional organism different genes be turned on and off at certain places and certain times in development. These requirements remain as a fully formed organism, where different tissues have distinctly different roles and must express only a subset of the full complement of genes. For example, intestinal tissues must produce digestive enzymes, which would not be appropriate for expression in another tissue, such as the skin.

48. Adrian Bird, "DNA Methylation Patterns and Epigenetic Memory," *Genes & Development* 16, no. 1 (2002): 6–21, doi: 10.1101/gad.947102.

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51. For the purpose of this paper, many of the technical complexities of these scenarios are assumed away. Pathogens (and all organisms) have evolved specific molecular structures and biological process to fit their specific life cycles. It is often the case that altering one trait causes follow-on effects in other biological processes. For example, increasing the ability of a natural pathogen to evade detection may also eliminate the ability of the new mutant strain to cause infection. Therefore, one is not able to simply modify one trait in an organism and magically create superweapons. Modification of biological agents takes significant time and effort. However, as our fundamental knowledge of biological pathways increases, it will be easier to target specific pathways while eliminating collateral effects in other areas of the organism.

Also ignored are many of the details that would require effective "weaponization" of a particular agent. Causing mass casualties with a biological agent requires an effective agent but also requires an effective delivery system. Affecting hundreds or thousands of individuals requires sophisticated delivery techniques. Assuring effective delivery mechanism and ensuring agent viability are often contradictory and represent a difficult balance to achieve.

However, while these scenarios are completely hypothetical and chosen arbitrarily, all of the technical capabilities described already exist and are "common" practice in high-end biological laboratories.

52. *Garage biology*, *DIY biology*, and *biohackers* are terms associated with a real community of amateur biologists who set up functioning microbiology laboratories in their homes. For only several thousand dollars, it is possible to acquire the equipment to do genetic manipulation of bacteria.

53. This scenario is not in itself revolutionary or novel, but the increase in knowledge and genetic engineering techniques make it easier, faster, and cheaper to do—while requiring less education.

54. Kevin M. Esvelt, Andrea L. Smidler, Flaminia Catteruccia, and George M. Church, "Concerning RNA-guided Gene Drives for the Alteration of Wild Populations," *eLife* 3 (July 2014), https://elifesciences.org/content/3/e03401; and Alanna Petroff, "Fighting the Zika Virus with Mutant Mosquitoes," *CNN Money*, 28 January 2016, http://money.cnn.com/2016/01/27/news/companies/zika-virus-oxitec-mosquito-brazil/index.html.

55. The cause of hive collapse is currently unknown, but it may be a combination of viral and fungal infections, mite infestations, and pesticide effects. Brian Dennis and William P. Kemp, "How Hives Collapse: Allee Effects, Ecological Resilience, and the Honey Bee," *PLoS One* 11, no. 2 (24 February 2016), e0150055, doi: 10.1371/journal.pone.0150055.

Deterring Emergent Technologies

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Abstract

This article examines the implications of emerging technological change on the multiplicity of future threats. Specifically, it examines the relevance of deterrence theory to both existing and new threats, some of which may surpass nuclear weapons in the risk they pose to the United States and humankind. It assumes science and technology growth will continue and will drive proliferation of advanced and potentially dangerous technologies. Rapid advances in biotechnology, nanotechnology, and directed energy may prove to be particularly dangerous. Deterring threats posed by nations, groups, and individuals will require new thinking regarding the application of deterrence theory—particularly deterrence by denial. The article concludes that groups and individuals will continue to gain access to new capabilities and technologies that once were considered the exclusive domain of nation-states. These technologies will enable group and individual adversaries to overcome the tyranny of distance and make it easier to discover, act, surprise, and target almost any place on Earth. Individuals will be more difficult than groups or nation-states to track, but the greatest likelihood of catastrophic attack is likely to be posed by groups. If the United States can ensure adversaries will be precisely attributed through greater system transparency and immunization, attacks may be deterred.[1]

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The rapidly changing nature of technology suggests that the world and the associated technological challenges it faces are changing in unprecedented ways.[2] It is not only the scope of technology change that is

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unprecedented but also its speed. This century will likely see 1,000 times the technological change of the last century, with each decade containing upwards of 70 times more technological development than occurred in the period from the dawn of time up until the year 2000.[3] This combination of great scope and speed of technological change means that the world of the 2030s will not merely be an extension of today. In many respects it will be fundamentally different. As a result, the greatest threats the world could face likewise represent a significant departure from past thinking. This article examines how the United States can best posture itself to deter nation-states, groups, and individuals from using biotechnology, nanotechnology, or directed-energy weapons. It begins by discussing the rapidly changing nature of emerging technology, its proliferation, and the developmental challenges associated with having only a small percentage of global research and development within the nation's military portfolio. It then delves into the nature of the threats across the three technological areas. The article discusses the types of attacks that will be possible over the next 20 years and what the effects could be upon the national critical infrastructure and the population; furthermore, it enables the reader to understand the breadth and depth of the challenges faced. It then introduces a structural model of deterrence based on the writings of many of the preeminent deterrence theorists of the past 60 years. This model dissects the concept of deterrence into its component parts and offers a useful analytic tool to determine how best to address each of the threats discussed. It concludes with a specific set of recommendations, while highlighting a few areas where further research or actions are necessary—particularly action by other governmental agencies to create an optimum deterrent posture.

The Changing Nature of Technology

Profound advancements are occurring across the entire range of sciences at an extremely rapid pace. As a result, the capabilities available to nation-state, group, and individual actors in the international arena will continue to expand at an ever-increasing rate. Driven by motives of profit, social pressures for ever-more-capable goods, as well as scientific curiosity and military necessity, continued exponential technological change is real and inevitable. One of the principal early findings, validated in earlier studies, is that many of the key technologies that will require deterrence in the future continue to evolve at an exponential rate. As with the number of transistors on a microprocessor and the number of Internet hosts, biology, nanotechnology, pulsed power, and other technical sciences are all racing ahead at ever-increasing speeds.

Research also shows that the United States and its military have an ever-decreasing say in the types of technology being developed. Seventy percent of all research funding happens outside the United States. Further, even among the 30 percent that happens within US borders, 70 percent of those technological developments are privately funded and are solutions or breakthroughs over which the military has no influence or sway.[4] Less than 4 percent of modern technological research is within the purview of the Department of Defense (DOD)—a radical departure from 50 years ago, when that number was nearly 50 percent.

Feeding this development is the collaboration enabled by the Internet. The increased use of the Internet as a source of collaboration results in scientific breakthroughs and technological applications being both increasingly civilian-developed and commercially and globally distributed, and these advancements are accelerating.[5] Moreover, the "half-life" of scientific secrets and their technological applications into militarily critical technologies are shrinking, and they are available to a multitude of actors, both state and nonstate. The result as we look to the future is that the technological dominance the United States has historically enjoyed may no longer be possible. By some measures of innovation, such as the number of major scientific articles published in peer-reviewed journals, China already surpasses the United States. While the United States continues to enjoy the best laboratory infrastructure in the world, our productivity is declining while others are rapidly improving their ability to innovate. This poses the danger of the United States losing the technological race.[6] Technologies formerly in the hands of only the wealthy nation-states are now being developed in what were once called developing countries.[7]

As a result of the decreasing cost of technology, groups and individuals now can acquire advanced capabilities that were once the purview only of states. Power is diffusing to the individual, meaning that attacks and battles of high probability may soon also be events of high consequence, thus changing the nature of warfare. Worse, these conflicts might become more common, meaning the future may be different from our past in significant ways. The world has already seen a rise in groups, including nongovernmental organizations, intergovernmental organizations, and terrorist organizations (such as al-Qaeda), many of which are able to affect outcomes on at least a regional basis. By 2008 these groups numbered at least 13,425 and possibly as many as 40,000.[8]

As technology becomes even less expensive, as automation increases, and as the ability of single individuals to create major effects is enhanced, the number of actors will grow still further. We are in a world where computers can pass the Turing test, meaning they cannot only assist individuals in carrying out tasks but also carry out these tasks by themselves.[9] As machines empower individuals and potentially even become capable of creating significant impacts on society, the number of potential actors undergoes yet another increase. By this measure, the world of 2030 has not hundreds of actors or even tens of thousands: It might have billions. The human race is likely to number between 8 and 9 billion by 2035, and this number itself may pale in comparison to the number of autonomous machines that might be roaming the planet by that time.[10] In short, the number of actors capable of making a major impact on the world stage will increase dramatically in the next 30 years.

Currently, we refer to the threats we face as *hybrid*. Whatever this future threat is (and there may be no good name for it), it is vastly more complex than anything experienced to date. The cause of the increase in the number of potential actors and of their increased potential capability is illustrated in economic theory. British science journalist Matt Ridley argues that the rapid evolution of human capabilities represents a significant research puzzle, as no other species has managed to adapt and conquer its environment so completely or quickly. Over time, this has led to the increased specialization of employment and the growth of these early communities into the megacities in which many of us live. The critical point is that the concentration of people escalated the interplay of knowledge that leads to increasing innovation. Ridley argues that the advent of the Internet is exponentially increasing the rate of innovation and now allows information sharing on a planetary scale, which will continue to increase our inventiveness as a species, to produce wealth, and to stimulate continued cultural change. From an economic perspective this argument is a story of good news. From the standpoint of biology, however, it has a darker side. As innovation increases at an exponential rate, our ability to understand, contain, and control new concepts and technology is threatened.[11] It would be an act of hubris to believe that we humans are somehow immune from this outcome.

Threats in the Age of Surprise

As a result of this increasing speed of interaction and data sharing, we have entered an "age of surprise." While it is possible to see the broad outlines of the future and to define the strategic planning space, this speed of change is making the specific details harder to see.[12] Whether we call these details turbulence or a form of chaos in complex systems, we have entered a period of inevitable surprises. We can discern the outlines of some in advance, including biotechnology, nanotechnology, and directed energy.[13] The key is to understand some of these potential surprises and know how to deal with the resultant challenges.

Biotechnology

The Human Genome Project, completed in 2003, identified all the genes in human DNA, and since then the threat has been rapidly evolving in biotechnology.[14] Today, it is possible to get your finger pricked and have your genomic code printed out with all the As, Gs, Cs, and Ts. Such a printout would reach about 20 feet high and would likely be meaningless both to you and to your doctor, but it is possible.[15] The step being worked on now is the "Rosetta stone" to those 20,000–25,000 genetic sequences—the part that determines how these genes produce the roughly 20,000 proteins that make each one of us a unique human being. This is called the Human Proteome Project, and it is well and truly under way.[16] Once the project is completed, pharmaceutical companies will be able to use these data to develop cures for many, if not all, genetic diseases. Illnesses like cystic fibrosis, muscular dystrophy, and cancer could all be eradicated. Already some cancers, particularly those such as leukemia, are being attacked by nanoengineered medicines based on an understanding of the ribonucleic acid structure of the underlying disease. The result for many patients is a long life with leukemia in remission. Many more such cures and treatments will follow in the years ahead. Unfortunately, this technology cuts both ways. Once the human genetic code is understood well enough to cure a genetic disease, it will also be understood well enough to engineer an illness for which no immunity can be found within the human genetic code. Leading scientists in our national laboratory system predict that by the year 2025, such capabilities will be resident in the hands of a well-trained microbiologist, whom they define as a master's degree holder from a major university. With a lab costing as little as $100,000, such an individual would be able to engineer a lethal pathogen inside a one-car garage or a small basement.

Lest this be thought of as only science fiction, such an event—though unintended and contained—already occurred with mice. In 2000, Australian scientists were attempting to modify the mouse pox virus to produce interleukin-4 in the hopes of stimulating the production of viral antibodies. This experiment had two unexpected results.[17] First, it failed to result in the production of the antibodies sought. Second, the resultant mouse pox strain had extraordinary lethality. Researchers arrived one morning to find every mouse in the laboratory dead, including mice immunized against the disease. The virus was 100 percent lethal, had overcome the immunity conferred by prior vaccination, and had spread to every mouse in the lab.[18] Although this incident was an accident, deliberate genetic modifications to existing viruses could produce the same result in other species—including our own.

Nanotechnology

The term *nanotechnology* is recent to science. Some versions of Webster's dictionary do not even contain a definition for the word.[19] Further, even within the discipline, its meaning causes controversy. Some have come to use nanotechnology to refer to any object or technology that is smaller than a micron (1,000 nanometers) in size. This misuse was partly an outgrowth of science fiction and partly of science still catching up to the concept.[20] Adding the marketing aspects of being able to label anything made with a coating or substance that contains small parts as being *nanotechnology*, the environment became ripe for misuse of the term. Here, nanotechnology refers to materials and substances that are constructed using processes to arrange particles of under 100 nanometers in size with submolecular precision, for which the important properties of the materials are governed largely by intermolecular (that is, van der Waals) forces.[21] Technology that merely involves scaling existing micromechanical processes to submicron scale is "nanoscale technology."

The field of nanotechnology offers three key advances as we move toward the future: (1) the nexus of biotechnology and nanotechnology, largely discussed above, (2) the creation of high-density energetic materials much more powerful than those developed to date and, (3) the development of nanomaterials that have specifically engineered properties, such as the ability to cause rapid corrosion, which could become a new class of weapons against systems and materiel. As indicated above, the first challenge with nanotechnology is the ability to precisely and deliberately create molecules of any design. As pharmaceutical companies are already demonstrating, once the genetic structure of a particular form of an illness is known, it is possible at the submolecular level to design medicines that can cure these diseases. As also mentioned, once the human genome is successfully decoded and the Rosetta stone is built, well-trained microbiologists will have the capacity to engineer pathogens for which, even at the genetic level, the human system has no built-in immunity.[22]

The second area of concern for future attacks deals with the production of high-density materials using precision nanotechnology to arrange molecular structures in a manner optimizing explosive power. While modern explosives are several times more powerful than trinitrotoluene (TNT), future explosives may be much more powerful still. One of the principal limitations of modern explosives is the availability of oxygen at the time and place of detonation. This causes the explosive to do two things. First, some explosive molecules may not ignite due to the oxygen-depleted environment and as such will reduce the total energy produced. Second, the explosive molecules that do not pair with the necessary oxygen immediately may still detonate but will do so after a short delay while they wait for additional oxygen molecules. This extends the duration of an explosion at the cost of reducing the initial blast effect. Using nanotechnology to pair oxygen atoms directly with the explosive atoms that require them would theoretically improve the efficiency of the explosive burn.[23] This same process could be used to enhance the thrust produced by rocket fuels, which are, in essence, controlled explosions themselves.[24]

While it is theoretically possible to achieve explosive yields of up to 1,000 times those of modern explosives, near-term advancements are likely to be much more modest.[25] Though nanotechnology is a rapidly advancing field, the ability to create the assemblers necessary to produce such explosives on a meaningful scale is currently limited; most scientists in the field believe that in the next 10–20 years an advancement of five- to tenfold is likely. Nonetheless, a tenfold advancement makes future explosives so powerful that the three-ounce bottle of liquid passengers are allowed to carry on board a civilian jetliner may have to be reduced to 0.3 ounces—only a few drops. Small, easily concealed explosives could pose significant risks to lives and property, and this miniaturization may result in a more-challenging threat in the years ahead.[26] Militarily, there are two positive aspects to this technology. First, the meticulousness needed to create these explosives would produce a precise and reliable yield, allowing for potentially greater accuracy and lower collateral damage from newer weapons designs. Second, the increased thrust potential emanating from these materials may significantly solve challenges associated with getting heavy objects into space. Historically, roughly 90 percent of all rocket mass has been either fuel or the systems that contain the fuel. The amount of thrust a unit of fuel can produce is called specific impulse (ISP). Increasing the energy content of the fuel five- to tenfold would increase the ISP proportionately and greatly reduce the amount of mass a rocket would need to devote to fuel and its associated system.[27] Though this dynamic has long been understood, the breakthroughs in nanotechnology may soon allow the dynamic to be exploited. While this may make it easier for man or robots to explore the stars or launch satellites, it would also make it easier for other actors to launch objects at long distances, posing yet another potential threat.

The last area where nanotechnology poses a potential threat is in designing molecules or nanoparticles to interact with materiel to cause severe damage to infrastructure or materiel. "White nanoparticles" are designed to specifically interact with their environment and to "pick up" any foreign debris located on the surface to which they are applied. In short, they are created as powerful agents designed to strip the surface of anything that should not be there. Similar agents could be designed to cause the degradation of materials and play havoc with critical components or infrastructure.[28]

Directed Energy

Two different forms of directed energy represent threats to military and civilian personnel. The first is the pulsed type, which includes such phenomena as pulsed high-powered microwaves, electromagnetic pulses, and a set of natural phenomena that mirror the effects of these two weapons types. The second type of directed-energy threat is continuous wave in nature. The power output of these weapons, usually referred to as lasers, has reached tactically significant levels in the past few years, and further developments are likely in the near future.

The discovery of the potential antielectronic utility of pulsed forms of energy came by accident. In 1962, shortly after the Soviet Union breached a nuclear testing moratorium, the United States tested a 1.4-megaton nuclear device 400 kilometers above Johnston Atoll in an experiment called Starfish Prime.[29] Approximately 1,300 kilometers away, in the Hawaiian Islands, street lights burned out, radio stations were knocked off the air, cars stopped due to burned-out generators and alternators, and some telephone systems were knocked off-line. The relationship between these events was not initially obvious and took some time to verify.[30] It is important to note that not every street light was disabled, that many cars still ran, and that some telephones still worked. Nonetheless, many systems stopped working, and only later did the reasons become clear. In 1967, both the United States and the Soviet Union (USSR) replicated these pulsed-energy effects. They discovered that nuclear detonations above the ionosphere would charge this region of the upper atmosphere and generate intense electromagnetic fields across the earth's surface. These fields fluctuate quickly and induce electric currents in all metallic objects they encounter. If the electricity generated is above the designed load for the system, the system shorts out and subsequently fails.[31] Fearing the effects of such weapons, the United States and the USSR together drafted the Outer Space Treaty (more formally, The Treaty on Principals Governing the Activities of States in Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies), which bans only weapons of mass destruction from space and does so because of the electromagnetic-pulse (EMP) phenomenon.[32]

However, a very similar phenomenon can be reproduced using a nonnuclear pulsed-power generator on the earth's surface. While physicists will be quick to point out that the precise shape of the pulsed waveform is different from that of a nuclear blast, its effects on electronics are nonetheless the same.[33] Inducing an electromagnetic field across wires, computer circuits, or any other conductive material produces electric current within the system. Like EMP, this current can wreak havoc with financial systems, computers, power distribution, and communications systems used to command-and-control military forces worldwide.

The level of damage done to these systems is related to the field strength of the magnetic field induced by the pulsed-microwave device and the sensitivity of the equipment.[34] It is important to realize that as computer-chip spacing becomes more compact in our quest to produce ever-more powerful and faster computers, the amount of energy needed to short out the computer circuits decreases with the square of the chip spacing. Stated more plainly, the ability to destroy or damage computer control systems is increasing exponentially as the computer chips become faster.[35] At the same time, our ability to store and generate pulsed power in the form of microwaves is also increasing exponentially. In 2003 it was possible to produce 20 gigawatts of pulsed-power output in a 400-pound device. Today several efforts are in the works on terawatt-class devices, some of which are explosively powered, representing a near 100-fold improvement in roughly a decade.[36] In 2002 conventional pulsed-microwave devices had relatively short ranges. Today small, portable, reusable weapons have ranges in the hundreds of meters. At the rate these technologies are changing, by the 2030s the ranges of these systems will be in miles or tens of miles, making them tactically and strategically significant.[37]

The other form of directed energy is continuous wave, the most common being lasers. While lasers have overpromised and under delivered for decades, this is no longer true. In November 2010, one of the authors placed an order for a small, handheld, category-IV, weapons-grade laser for $299. To the researchers' surprise, the order processed on "Black Friday," a shopping holiday after Thanksgiving, resulting in the "three-for-one" special deal. We paid less than $100 for each of the three lasers that arrived about six weeks later. The blue variant of this laser measures approximately 20 centimeters long and approximately five centimeters in diameter, weighing about 250 grams. It is a potentially lethal device, but its greatest dangers come from its ability to permanently blind a person in less than 0.25 seconds at a range of approximately 150 meters. It is capable of melting plastic and setting flammable materials ablaze (451° F or 233° C).[38] The laser runs off a single lithium-ion battery, roughly the size of a standard AA battery, which enables the laser to operate continuously for 120 minutes on a single charge. A company operating in Hong Kong began producing and marketing the laser in the fall of 2010. At that time, only Malta had definitive restrictions on the sale or importation of this device.[39] In the United States, importation was legal. Though not directly attributable to this laser, in the first nine months of 2010, before this laser hit the market, the United States had 299 lasing incidents against civilian aircraft. There were 2,700 more in the last three months of that year. Blinding incidents have also increased in other countries, including some attacks on motorists.[40]

Meanwhile, lasers for aircraft and weapons applications have reached tactically significant power levels. Chemical oxygen iodine lasers (COIL) have been designed for applications ranging from missile defense to ground attack. The airborne laser system, which the DOD recently decommissioned, was a megawatt-class system, roughly 1 million times more powerful than the handheld laser above. Air Force Special Operations Command placed a much smaller COIL device on board a C-130 aircraft and successfully disabled targets on a weapons range, including a truck.[41] As with pulsed-power devices, laser efficiency and effectiveness are continuing to improve. Small handheld devices powerful enough to blind or kill soon will be in the hands of those who may seek to create fear or terror. Larger lasers, with speed-of-light kill capability, will likewise be obtainable via arms markets well within the next 20–30 years.[42] Directed-energy research is continuing in several countries and will pose a risk to satellite operations in the very near future.[43] Lasers that can dazzle or destroy satellites, likely all the way to geostationary orbit, may be fielded by the 2030s. The result is that space assets, both military and civilian, are and will increasingly be vulnerable to attack, either from the ground or from space. The challenge becomes how the United States deters these threats.

Deterring Emerging Threats

To deter the technological threats of biotechnology, nanotechnology, and directed energy one must first understand deterrence concepts and deterrence theory; extensive literature covers both conventional as well as nuclear deterrence theory. [44] The model below depicts two predominant aspects of deterrence and the relationship between them.

The focus during the Cold War was mainly on the left half of the model—"Fear/Retribution." This thinking made sense because during the Cold War time frame, the treaties in effect limited each side (the United States and Soviet Union) to 100 ballistic missile interceptors.[45] Since each side in the Cold War had vastly more than 100 nuclear weapon systems, there was an implicit assumption that it would be impossible to deny the opposing side the ability to carry out a massive strike that would inflict severe damage on the opponent should it choose to do so. As a result, the "denial" side of the equation was limited in value to only that necessary to ensure a retaliatory capability existed. There was no method by which one could deny the initial attack, and as such, much of the denial side of the model was ignored, leaving mutual destruction or unacceptable levels of damage (fear) as the linchpin upon which deterrence was based. It is important to recognize that the theory itself is structurally sound, but in deterring emerging technologies the relative importance of the two sides of deterrence theory changes. The difference is, with many of the threats we face in the future, there are opportunities to prevent or protect from attacks, to thwart the goals of prospective adversaries, and to deter or hinder the development of these capabilities in the first place. These key elements of the right-hand side of the model take on new levels of importance in the future and thus constitute a change in the way in which the DOD needs to operate.

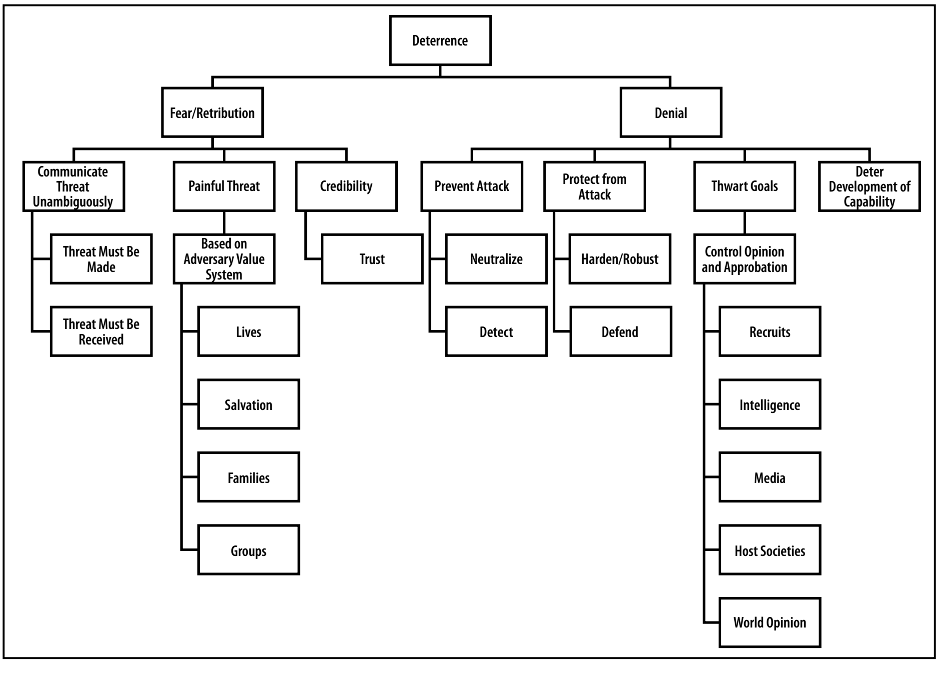

Figure 1. A structural model of deterrence theory

In operationalizing the model against the array of future threats, many of which are conventional, we turned to an equation verbally described in John J. Mearsheimer's book *Conventional Deterrence*. Mearsheimer argues that the failure of deterrence is specified as a calculus in the mind of the actor to be deterred, referring to this calculus as "the attacker's fear to the consequences of . . . action."[46] While he describes this calculus in great detail, it can be simplified as a mathematical expression. An actor is deterred if the equation depicted in figure 2 holds.

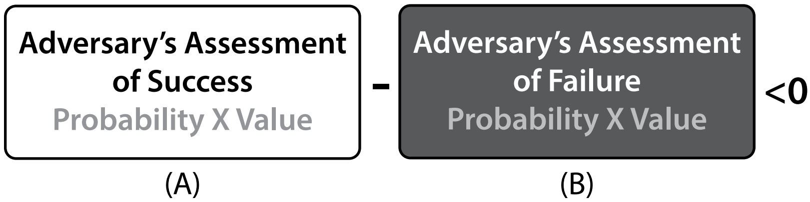

Figure 2. The deterrence equation

Mearsheimer argues that several factors play in this calculus of whether deterrence will succeed. The first is the adversary's perception of the value of success itself—the gain to be incurred by attacking. The second factor is the probability that the attack will succeed. The product of these two elements comprises the potential adversary's assessment of success (A). Only if the assessment of failure is greater than that of success will a rational actor be deterred. This failure assessment is calculated in much the same manner—the cost of failing is multiplied by the probability of failure. If the failure assessment (B) is the greater of the two terms, then the value of the equation is less than zero, and the actor is deterred.[47] Some assumptions are embedded in this calculus that must be highlighted in light of the new threats. First, it assumes the actor is rational. This does not mean the actor's calculus is the same as one's own or that it matches one's values—only that it has a rational basis underpinning it. Second, it assumes that one can attribute the attack to the proper actor. While in the nuclear era this was relatively easy, it has proven much more difficult in newly created artificial domains such as cyberspace. It is crucially important to explore what happens to the deterrence equation in the absence of attribution. Should attribution be problematic, it tilts both parts of the deterrence equation in favor of the potential aggressor. An inability to attribute an attack means the probability of successfully carrying it out likely rises or at a minimum remains the same. The probability of incurring punishment clearly diminishes because without attribution it is impossible to know toward whom the punishment should be directed. As a result, in the absence of proper attribution, the deterrence equation tilts in favor of the potential adversary, making successful deterrence less likely.

Of equal concern is what happens when attribution is either assumed or figured incorrectly. A failure to properly attribute often leads to simpleminded decisions along the lines of what actors expect.[48] Further, in the absence of data or in the midst of uncertainty, decision makers tend to engage in more violent modes of coping with the ambiguity.[49] These dynamics were tested in exercises conducted in conjunction with this research—exercises that placed participants in a war game in a position of relative uncertainty with regard to adverse conditions experienced by the United States and its allies. Even though sufficient data were available to the participants to uncover the actual actors, the vast majority of the participants attributed the hostile actions to the wrong actor. In a real-world situation, such misattribution can have disastrous consequences.

Getting attribution correct is essential not only to realize deterrence but also to avoid unintended conflict. Complicating the problem of attribution is the fact that the time to respond to attacks from several emerging threats is much less than the reaction time that was available in the nuclear-deterrence era. As a result, the time necessary to observe events, orient to these events, decide on a course of action, and then act (OODA) on that decision is shrinking.[50] The OODA loop decision cycle is rapidly collapsing into an OODA point. With several new technologies operating either at or near the speed of light, this decision loop is moving toward a point requiring much more rapid capabilities to observe and attribute incoming attacks. The nation-states that comprise our global security system are similarly chaotic and capable of rapidly tipping from one state to the next. In the end, the human system in which we must deter is complex and chaotic while the credibility of deterrence hinges on the capacity to accurately attribute such actions at ever-increasing speeds.

The Delphi Study and Results

To better understand where the greatest challenges for deterring emerging technologies lay, we conducted a formal and informal Delphi study using three questions.[51] It drew upon participants who had studied the technologies and had a working knowledge of deterrence theory and military strategy. Each question explored the three technologies and parsed the responses to separate dynamics that differed among nation-states, groups, and individuals.

The first question asked the respondents to use a Likert scale of one to five (very easy, easy, neutral, difficult, and very difficult) to rate the level of difficulty of deterring nation-states, groups, and individuals from launching an attack using each of the technologies shown in figure 3. The results show that it is more difficult to deter individuals, regardless of technology, than to deter nation-states. In addition we found that bio- and nanotechnologies would likely be the most difficult to deter. Further, although the slope changed for each technology, the relationship across the three categories took on a mostly linear shape. In general, the study participants believed nation-states and groups placed value on their respective reputations. Moral constraints to use force and the results of international approbation act most strongly on nation-states.[52] Yet for groups, especially the larger ones, the reputational issues were strong enough to make them easier to deter than small groups and individuals. Individuals would be least affected by international norms and thus the hardest to deter.

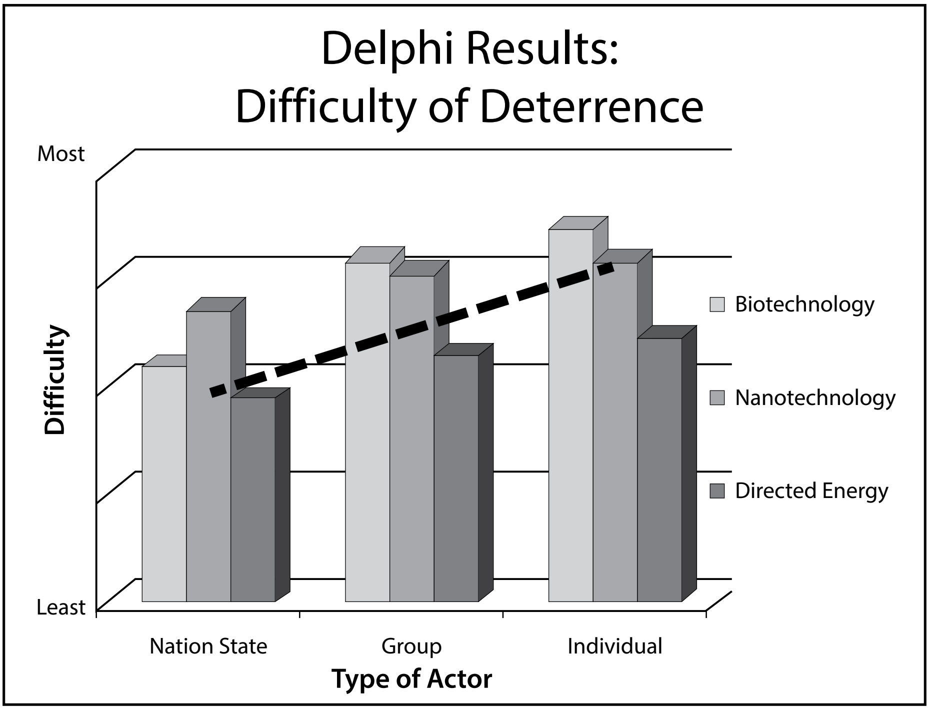

Figure 3. Difficulty of deterrence: Delphi results

The second question focused on the difficulty of attribution. As with the previous question, this one was parsed by both type of actor and technologies involved.

The depiction in figure 4 takes on the same shape as the previous one but for different reasons. Here, individuals were considered the most difficult to attribute across all technologies since they were the most likely to conduct an attack and successfully avoid leaving a distinguishing trail that would lead to properly attributing the source of the attack. States, on the other hand, because of their size and the bureaucracies that must approve these actions, often leave traceable indications of their responsibility for certain actions. Additionally, in some cases, the research efforts necessary to launch attack programs by nation-states in these areas would require funding of sufficient size to make it possible to trace the program. Biological attacks were considered problematic because tracing the source of a disease or pathogen may be difficult, especially if it has a considerable incubation period. Should such an agent be distributed at a major transit hub, such as a major international airport, viruses would be hard to trace to their origins since the passenger traffic would leave a very large number of potential paths to trace.[53] Nanotechnology threats also were considered difficult because they are small enough in size that they could remain dormant for extended periods, leaving great doubt as to when they were positioned.

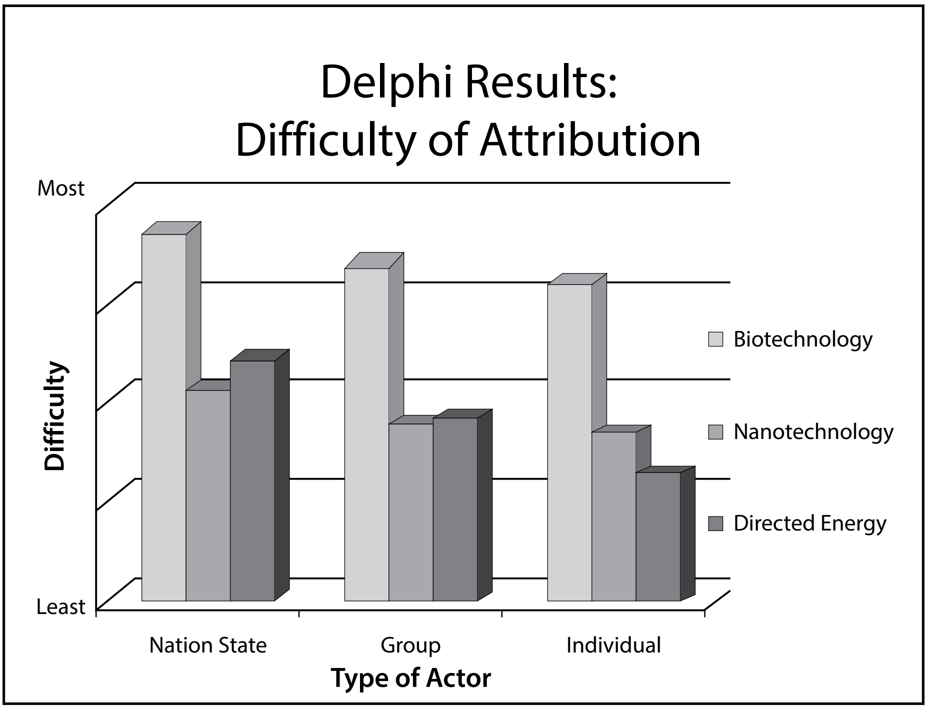

Figure 4. Difficulty of attribution: Delphi results

The last question regarded the likelihood of attack. Here, definitions proved important insofar as we were interested in the likelihood of only very large destructive or catastrophic events. For this question a "catastrophic" attack was considered one that "threatens national survival or eliminates the ability to accomplish the mission." A "destructive" attack was one that "seriously impacts the ability to function or significantly degrades mission performance." The results are depicted in figure 5, which contains three patterns within the data that are worthy of explanation. First, the greatest perceived threats were based on biotechnology. This danger is significant due to the relatively unprotected and very incomplete infrastructure to detect novel pathogens or viruses. Second, the graph has a central "hump," showing a greater probability of catastrophic or destructive attacks coming from groups than from individuals or nation-states. This created a curve that placed the maximum likelihood for attack at the group level. It should be noted that had we lowered the damage threshold of interest, it is likely that individuals would have scored much higher. Lastly, for nanotechnology and directed energy, nation-states were considered the most likely to attack catastrophically because we deemed it unlikely that even groups would have the resources to attack using these weapons on a massive scale.

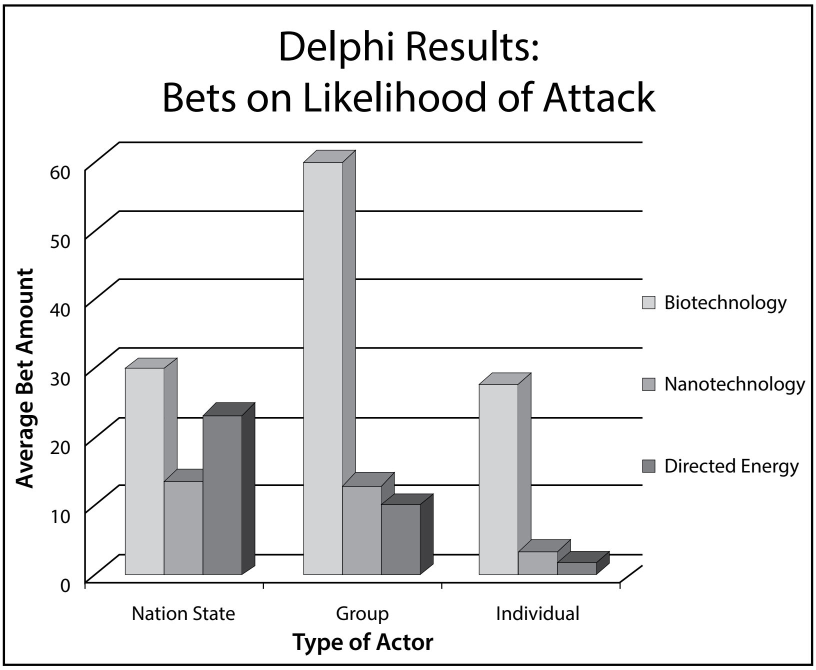

Figure 5. Likelihood of catastrophic attack: Delphi results

Findings and Implications

Deterring future technologies of adversaries remains a great challenge for the DOD, particularly concerning biotechnology, nanotechnology, and directed energy. Solving this challenge will require two specific concepts: transparency and immunization.

Increased transparency is necessary to facilitate proper attribution and early warning of attack. Transparency contains three elements: (1) technical developments that aid in tracking people and objects through space and time, (2) ongoing innovation in this area, and (3) the advent of new command-and-control concepts. With the development of the internet, most data—public and private—is archived for retrieval. Even when websites are updated or personal data removed, the old data is still available and can be retrieved.[54] The result is that anything which has been on the Internet can often still be found, enabling the searching for information not only across geographic space but also across time. These searches can synchronize raw data as well as pictorial information; they archive public (government) as well as private (personal) web postings. In short the technological developments are moving us toward transparency. As this enormous data set becomes available on the Internet, new innovations will be necessary to use it. Some of the necessary algorithms already exist and are able to examine patterns of human behavior and flag for analysis those activities that are unlike others. Such algorithms can be useful for enabling business to foresee the next major consumer product or for enhancing security. One such set of algorithms has been developed as part of the Risk Assessment and Horizons Scanning system in Singapore.[55] That city-state has developed an analyst-intensive process that involves environmental scanning for data, provides indicators of possible activity, enables the conduct of sentiment analysis, and helps with data fusion and analysis that leads to scenario development and the development of strategies. While not fully automated, the system provides "insights to emerging risks and opportunities with national security implications."[56] With a world of data available and the algorithms to flag events that may be indicators of risks, proper command and control can ensure that risks are properly assessed. Global command-and-control capability becomes the last element of a new transparency system. As data suggest that a risk may be emerging in a part of the world, the command and information exchange systems—in conjunction with well-trained leadership—enable analysis, further research, and assessment of the risks as they emerge.

These data are fused and processed using advanced algorithms that build on work already done. These algorithms will be designed to highlight or flag unusual patterns of behavior worthy of human analysis. Upon seeing such a signal, the analyst initiates tracking. The analyst drills into the data to determine if there is a concern that rises to the level of a threat to US facilities or interests. If such a threat exists, an analyst does additional analytical work with the data to attribute the threat to a specific actor or set of actors and then characterize that threat, including identifying its capabilities, operating procedures, and location. At that point, the government has many options available to deter a potential adversary. Depending on the nature of the threat and how early in the planning process an attack has been identified, the options may range from merely warning the individuals that they have already been discovered to potentially arresting or striking them if the threat they pose is more imminent. As these actions are taken, ripples or perturbations in the networks associated with these actors will likely appear within one or more of the streams of data. Additional fusing of data and repeating the above process will also flag other potentially dangerous actors associated with the initially discovered adversary for further analysis. Iterating this process will soon make obvious to actors who seek to hurt the United States that their likelihood of success has decreased, shifting the deterrence calculus in our favor.

From this proposed operational concept, transparency should be thought of as a second pillar of deterrence since it has benefits similar to those of attack and defense. More importantly, transparency has a deterrent quality all its own. It is important to understand that transparency is about knowledge rather than control. Along with the ability to strike globally, transparency has the potential to radically alter adversaries' deterrence calculus. If they believe their actions will likely be discovered and attributed and then punished severely, then the attack will likely be deterred. As a result of the development and proliferation of technologies that can create catastrophic effects over the next 10–20 years, transparency and the associated concept of attribution will be essential. Moreover, as a requirement it will drive defense procurement spending.

Unfortunately, transparency is a two-way street and by itself it does not fully address all the aspects of deterrence by denial. It is likely adversaries will have some level of transparency against the United States. As a result of this transparency, we need a set of means to deny potential adversaries a chance to succeed, even when our forces or infrastructure are in known locations. In short we need to deny success, and to do this, we need a second concept called immunization.

Immunization

As it applies to emerging technological threats, immunization is a protective measure that reduces attack effectiveness. Similarly, a nation-state properly immunized against attack will not suffer significant damage, even if an attack is launched against it. For the United States, this immunization process involves implementing physical safeguards around certain critical infrastructure. It involves creating backup methods of operation and functional resilience that result in little or no degradation to operations should an attack occur, creating strategies that enable flexible options to mitigate the effects of an attack. It also results in the development of cognitive resilience within the populace and the military, creating a mind-set in which, even if an attack occurs, there is not a disproportionate psychological reaction to the strike.

As threats become more numerous and span increasingly large technological sets, immunization will require time, resources, and practice to attain. The methods of immunizing computer systems will be different from those of immunizing the populace against a biological pathogen. Nonetheless, the country must be prepared to do so. If we can achieve a level of immunization that minimizes the gains realized by attacking the United States and its interests abroad, then the deterrence calculus shifts in favor of the defender, and the nation becomes more secure. To insure that immunization actions are considered in that calculus, demonstrations of these capabilities will likely be required.

Issues for Other Departments

Because of the breadth of challenges that will confront the United States in the 2030s, this is much more than a Department of Defense problem. There are issues for the departments of Homeland Security (DHS), Transportation, Health and Human Services, and Commerce, as a minimum. The DHS is responsible for the defense of our national infrastructure and air transport system. Consequently it needs to understand the potential impact that directed energy will have on our electrical and banking systems. The DHS is also responsible for airline safety. Nanotechnological explosives will soon increase the potential for very small amounts of a substance to create very large explosions. While there is substantial public backlash against strictures such as the three-ounce-bottle limits on commercial aircraft, this problem is about to become worse. The DHS will need to develop methods of detecting which compounds can explode and which cannot—and further, detect these when they may be chemically new materials or something nanoengineered in an adversary's laboratory. The Department of Transportation has this same requirement but with respect to our major highways and bridges. The destruction of all bridges that cross the Missouri–Mississippi river system with nanoexplosives is something that must be guarded against as well.

The one potential extinction-level event discussed above is biological attack. Previous studies have recommended major efforts to enable rapid detection and decoding of new genomic structures along with the ability to quickly prototype and produce vaccines.[57] We stated then and reiterate now that a major project is needed on biogenetics to ready the nation and the world to rapidly respond to the outbreak of a novel virus, whether man-made or a natural mutation, within a matter of hours instead of the nearly one year it currently takes to develop the annual influenza vaccine. However, implementation lies within the purview of the Centers for Disease Control and the National Institutes of Health.

Conclusion

It is important to note that deterrence by denial is not new. It has been a part of deterrence theory for over 50 years, but it is more important now than it has been in the past. In short, we are entering a world where the proliferation and cheapening of potentially harmful technologies will impose costs on those nation-states that value protecting their populace. The panoply of new threats increases the requirements for the services to work together to create effective transparency and immunization to provide resilience. As we do this, we need to understand not only who is theoretically responsible for certain mission sets but also who will accomplish them. While the threats in this study may come from terrorists, what is necessary to defeat this threat bears little resemblance to the types of combat in which we have been engaged over the past 15 years. Further, technology is changing at such a pace that those who fail to make a concerted effort to stay abreast of new developments will find their thinking quickly rendered obsolete. The scope of the threats we may face from emerging technologies is disturbing. Properly addressing these two broad areas will make attacks easier to attribute, adversary opportunities easier to deny, and adversary success harder to achieve. Collectively these tilt the deterrence calculus in favor of the United States, making it much less likely that the adverse and severe consequences of the threats discussed above will ever be endured. SSQ

Notes

1. The authors want to thank the scientists, researchers and policy analysts of the US Air Force and National Laboratories. The authors also wish to extend a special thank-you to academic leaders and government officials who provided commentary and insights. Among these are John Mearsheimer and Bob Pape of the University of Chicago; Gen Mike Hayden, USAF, retired; and Dennis Bushnell of NASA. Air War College students involved in the study included Lt Col Joel Almosara, Col David Blanks, Lt Col Darren Buck, Lt Col Patrick Burke, Col Christopher Kinnan, Col Tom Coglitore, Lt Col Miguel Colon, CDR Peter Falk, Col Michael Finn, Col John Gloystein, Col Christopher Hauth and Col Wiliam Jensen. The team of 35 researchers and five faculty members from Air War and Air Command and Staff Colleges began with a search across science and technology, education and training, governmental policy, organizational culture, national strategies, and military studies literatures. The research team was deliberately selected for its breadth of expertise across all relevant military specialties. These researchers visited Sandia, Los Alamos, and Lawrence Livermore national laboratories. In addition the team visited seven of the 10 Air Force Research Laboratory directorates, including Space Vehicles, Directed Energy, Materials Sciences, Human Factors Engineering, Propulsion, Air Vehicles, and Sensors. In each, senior scientists made presentations, and the researchers had time to discuss and interview these scientists regarding current projects, including those that were in the conceptualization stages. This research helped define the range of technologies likely to be available in the field in the 2030–35 time frame for which this study was commissioned.

2. John L. Petersen, "Punctuations," *FUTUREdition* 15, no. 8 (30 April 2012), http://www.arlingtoninstitute.org/fe-archive-volume-15-number-8. Also published as the foreword in Finley Eversole, ed., *Infinite Energy Technologies*: *Tesla, Cold Fusion, Antigravity and the Future of Sustainability* (Rochester, VT: Simon & Schuster, 2012).

3. Ray Kurzweil, *The Singularity Is Near* (New York: Penguin Books, 2005), 10–50.

4. T. Michael Moseley, *Blue Horizons: Horizons 21 Study Report* (Maxwell AFB, AL: Center for Strategy and Technology, Air War College, 2007). These numbers have not changed much since 2007, as verified in a 2012 study by Battelle Corporation. See Martin Grueber et al., "2012 Global R&D Funding Forecast," *R&D Magazine*, 16 December 2011, http://www.rdmag.com/articles/2011/12/2012-global-r-d-funding-forecast. Grueber and company point out that US research and development spending will top $420 billion but that only $128 billion will be driven by the government—a total of 29 percent. The United States continues to hold about 30 percent of the global research and development share.

5. Air War College papers written on this topic include: Christopher Coates, *The Air Force in SILICO: Computational Biology in 2025* (Maxwell AFB, AL: Air University Press, 2007); Shane Courville, *Air Force and the Cyberspace Mission: Defending the Air Force's Computer Network in the Future* (Maxwell AFB, AL: Air University Press, 2007); Mark S. Danigole, *Biofuels: An Alternative to US Petroleum Dependency* (Maxwell AFB, AL: Air University Press, 2007); and Vincent T. Jovene, *Next Generation Nanotechnology Assembly Fabrication Methods: A Technology Forecast* (Maxwell AFB, AL: Air University Press, 2008).

6. Organisation for Economic Co-operation and Development (OECD). The United States ranks last among OECD countries in reading, 27th in math (between Russia and Portugal), and 22nd in science (between Iceland and the Slovak Republic).

7. Thomas L. Friedman, "The Ten Forces That Flattened the World," in *The World Is Flat: A Brief History of the 21st Century* (New York: Farrar, Straus and Giroux, 2007), 51–199.

8. Estimates of the numbers of these groups vary widely. The lowest estimate the authors encountered in their research was 13,425. See *The United Nations Today* (New York: United Nations Department of Public Information, 2008). Mainstream estimates are in the range of a few tens of thousands, with some upper-end estimates around 60,000. See Marlies Glasius, Helmut-Anheier, and Mary Kaldor, "Introducing Global Civil Society," *Global Civil Society Yearbook 2001* (Oxford, UK: Oxford University Press, 2001), 2–38.

9. Two computers have, arguably, successfully passed a version of the Turing test wherein a computer mimics human behavior so closely that in a blind test observers cannot discern which actor in a lineup is the computer. The most recent event was in 2014, when "Eugene Goostman," a chat bot designed by Vladimir Veselov and Eugene Demchenko, successfully convinced judges after a five-minute interview that it was a human. "Turing Test Passed by Computer," *CBCNews*, 9 June 2014, http://www.cbc.ca/news/technology/turing-test-passed-by-computer-1.2669649. For details on the nature of the test, see Alan M. Turing, "Computing Machinery and Intelligence" in *Parsing the Turing Test: Philosophical and Methodological Issues in the Quest for the Thinking Computer*, ed. Robert Epstein, Gary Roberts, and Grace Beber (Dordrecht, Netherlands: Springer, 2009), 23–66. The other computer sometimes argued as having passed the test is Watson. See Ray Kurzweil, "The Significance of Watson," *Kurzweil Accelerating Intelligence* (blog), 13 February 2011, http://www.kurzweilai.net/the-significance-of-watson. It is worth noting that Kurzweil believes that the Loebner threshold for passing the Turing test is too low but that genuine human intelligence will be reached by 2029.

10. US Census Bureau, Department of Commerce, "U.S. & World Population Clocks," accessed 12 May 2012, http://www.census.gov/main/www/popclock.html.

11. Matt Ridley, "Humans: Why They Triumphed," *Wall Street Journal*, 22 May 2010, http://online.wsj.com/article/SB10001424052748703691804575254533386933138.html; Matt Ridley, *The Rational Optimist: How Prosperity Evolves* (New York: HarperCollins, 2010), and Anthony Hallam and Paul B. Wignall, *Mass Extinctions and Their Aftermath* (Oxford, UK: Oxford University Press, 2002). Based on Hallam and Wignall's calculations, the combined extinction loss from the five major extinction events (End-Ordovician [84 percent], Late Devonian [83 percent], End Permian [95 percent], End Triassic [80 percent], and End Cretaceous [76 percent]) would be 99.994 percent. This figure does not include the background extinction rate of those species that died out between these events, which would raise this figure still higher.

12. Peter Schwartz, *The Art of the Long View* (New York: Doubleday, 1991), 17–169.

13. Peter Schwartz, *Inevitable Surprises: Thinking Ahead in a Time of Turbulence* (New York: Gotham Books, 2003).

14. Human Genome Program, Office of Biological and Environmental Research, Department of Energy, "Human Genome Project Information," 21 March 2014, http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml.

15. Michael B. Miller, "How Tall of a Stack of Paper Would We Need to Print Out an Entire Human Genome?," working paper (Minneapolis: Division of Epidemiology and Community Health, University of Minnesota, 15 October 2005), http://bio4.us/biotrends/human_genome_height.html.

16. Human Proteome Organisation (HUPO), "Human Proteome Project (HPP)," HUPO, 21 March 2012, accessed 11 June 2016, http://www.hupo.org/research/hpp/.

17. BBC, "Mouse Pox or Bioweapon?" *BBC World Service*, 17 January 2001, accessed 12 June 2016, http://www.bbc.co.uk/worldservice/sci_tech/highlights/010117_mousepox.shtml.

18. William Bains, *Biotechnology from A to Z* (New York: Oxford University Press, 2004), 52.

19. The dictionaries issued to the authors by the federal government are among those that do not yet contain an entry for nanotechnology.

20. J. Hall Stores, *Nanofuture: What's Next for Nanotechnology* (Amherst, NY: Prometheus, 2005), 15–22.

21. Ibid, 15–51.

22. Leading biological scientists, interviews.

23. Witold Gutkowski and Tomasz A. Kowalewski, *Mechanics of the 21st Century: Proceedings of the 21st International Congress of Theoretical and Applied Mechanics*, Warsaw, Poland, 15–21 August 2004 (Dordrecht, Netherlands: Springer, 2005), 379; and Oleg Vasylkiv, Yoshio Sakka, and Valeriy V. Skorokhod, "Nano-Blast Synthesis of Nano-size CeO2-Gd2O3 Powders," *Journal of American Ceramic Society* 89, no. 6 (June 2006): 1822–26.

24. John W. Cole, Isaac F. Silvera, and John P. Foote, "Conceptual Launch Vehicles Using Metallic Hydrogen Propellant," *American Institute of Physics Conference Proceedings* 969 (2008): 977–84.

25. It is interesting to note that a yield increase of 1,000-fold would create a set of conventional ordnance with yields in excess of the bombs dropped on Hiroshima and Nagasaki during World War II. This would necessitate revisiting the question of what constitutes a weapon of mass destruction.

26. Ancel Yarbrough, *The Impact of Nanotechnology Energetics on the Department of Defense by 2035* (Maxwell AFB, AL: Air War College, 2010), http://www.au.af.mil/au/awc/awcgate/cst/bh2010_yarbrough.pdf.

27. Henry D. Baird et al., "Spacelift 2025: The Supporting Pillar for Space Superiority," in *Air Force 2025*, vol. 2 (Maxwell AFB, AL: Air University Press, 1996), 117–50.

28. Of course nanotechnology, like biotechnology above, can cut both ways. The same basic science that can create nanocorrosives can also create nanocoatings that would make systems resist corrosion. There are over 30,000 scholarly articles on this subject. Among the more heavily cited are S. Radhakrishnana, C. R. Sijua, Debajyoti Mahantab, Satish Patilb, and Giridhar Madras, "Conducting Polyaniline-nano-TiO2 Composites for Smart Corrosion Resistant Coatings," *Electrochimica Acta* 54, no. 4 (30 January 2009): 1249–54; Lidia Beneaa, Pier Luigi Bonorab, Alberto Borelloc, and Stefano Martelli, "Wear Corrosion Properties of Nano-Structured SiC-Nickel Composite Coatings Obtained by Electroplating," *Wear* 249, no. 10–11 (November 2001): 995–1003; and Martin Kendig, Melitta Hon, and Leslie Warren, " 'Smart' Corrosion Inhibiting Coating," *Progress in Organic Coatings* 47, no. 3 (September 2003): 183–89.

29. House of Representatives, *Electromagnetic Pulse Threats to U.S. Military and Civilian Infrastructure: Hearing before the Military Research and Development Subcommittee of the Committee on Armed Services*, 106th Cong., 1st sess., 7 October 1999 (prepared statement of Lowell Wood, member of director's technical staff, Lawrence Livermore National Laboratory), 30–36. See also John P. Geis II, *Directed Energy Weapons on the Battlefield: A New Vision for 2025* (Maxwell AFB, AL: Center for Strategy and Technology, Air War College, 2003), 8–11.

30. Ibid.

31. A. Barrie Pittock et al., "Direct Effects of Nuclear Detonations," in *Environmental Consequences of Nuclear War, vol. 1*, eds. A. Barrie Pittock, Mark Harwell, and T. C. Hutchinson (New York: John Wiley and Sons, 1986), 1–23.

32. Geis, *Directed Energy Weapons*, 9.

33. Pittock et al., "Direct Effects of Nuclear Detonations," 17–20; and Geis, *Directed Energy Weapons*, 11–14.

34. For a discussion on the precise field strengths to cause specific amounts of damage, see Geis, *Directed Energy* Weapons, 11–15.

35. There is a method to harden computer chips against this phenomenon, but such hardening is expensive, and very few foundries in the world produce these chips.

36. Carlo Kopp, "The Electronmagnetic Bomb—A Weapon of Electrical Mass Destruction," *Air and Space Power Journal: Chronicles Online Journal*, 1996, http://www.airpower.au.af.mil/airchronicles/cc/apjemp.html.

37. Geis, *Directed Energy Weapons*, 11–15.

38. No endorsement of the product being discussed is intended or implied. The products listed here are dangerous and require substantial training to handle safely. For academic purposes, additional data may be found at Wicked Lasers, "Spyder Arctic," accessed 12 June 2016, http://www.wickedlasers.com/arctic. Following our initial research, a new company began marketing an even smaller laser that is much more powerful than the Spyder. Its laser creates temperatures of up to 850 degrees at the point of lasing, which the newly upgraded Arctic Laser (now $199) at 2 watts of power is now also capable of attaining.

39. The authors searched for importation restrictions on lasers across the world. While it is possible some were missed, after an exhaustive search, only the country of Malta had laws we could locate that prevented the importation of a category-IV device.

40. The authors presented early findings at the Aircraft Survivability Conference in Berlin, Germany, 13 October 2010. Discussions with members of the German parliament who were present revealed concern over recent lasing incidents on the autobahn. These government leaders were unaware of the newly marketed handheld device.

41. Matthew Potter, "Boeing Video of Advanced Tactical Laser (ATL) Aircraft," *Defense Procurement News*, 2 October 2009, accessed 12 June 2016, http://www.defenseprocurementnews.com/2009/10/02/boeing-video-of-advanced-tactical-laser-atl-aircraft.

42. Geis, *Directed Energy Weapons*, 16.

43. William Diehl, *Continued Optical Sensor Operations in a Laser Environment* (Maxwell AFB, AL: Air War College, 2011), http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA570475.

44. The authors believe this may be the first structural model of deterrence, laid out in a manner that would invite future value model-based research. We derived the model primarily from the following scholars and works (the list is not exhaustive): Thomas C. Schelling, *Arms and Influence* (New Haven, CT: Yale University Press, 1966); Paul Huth and Bruce Russett, "What Makes Deterrence Work? Cases from 1900–1989," *World Politics* 36, no. 4 (July 1984): 496; Lawrence Freedman, *Deterrence* (Malden, MA: Polity Press, 2004); Christopher Layne,

"From Preponderance to Offshore Balancing," in *The Use of Force: Military Power and International Politics*, 7th ed., ed. Robert J. Art and Kenneth N. Waltz (Lanham, MD: Rowman and Littlefield Publishers, 2009), 311–26; Andrew J. Goodpaster, C. Richard Nelson, and Seymour J. Deitchman, "Deterrence: An Overview," in *Post–Cold War Conflict Deterrence* (Washington, DC: National Academy Press, 1997), 10–38; Keith B. Payne, *The Fallacies of Cold War Deterrence* (Lexington: University Press of Kentucky, 2001); Graham Allison and Philip Zelikow, *Essence of Decision: Explaining the Cuban Missile Crisis*, 2nd ed. (New York: Longman, 1999); John P. Geis II et al., *Discord or "Harmonious Society"? China in 2030*, (Maxwell AFB, AL: Air University Press, 2011); Bruce Russett and Alan C. Stam, "Courting Disaster: An Expanded NATO vs. Russia and China," *Political Science Quarterly* 113, no. 3 (Fall 1998): 361–82; Keith B. Payne, *The Great American Gamble: Deterrence Theory and Practice from the Cold War to the Twenty-First Century* (Fairfax, VA: National Institute Press, 2008); Union of Concerned Scientists, "Nuclear Weapons & Global Security: History of Russia's Anti-Ballistic Missile System," 2012, http://www.ucsusa.org/nuclear_weapons_and_global_security/missile_defense/policy_issues/history-of-russias.html; Yao Yunzhu, "Chinese Nuclear Policy and the Future of Minimum Deterrence," *Pacific Forum CSIS* 6, no. 2 (September 2005): 31–40, http://csis.org/files/media/csis/pubs/issuesinsights_v06n02.pdf; Kenneth N. Waltz, "Nuclear Myths and Nuclear Realities," in *The Use of Force: Military Power and International Politics*, 6th ed., eds. Robert J. Art and Kenneth N. Waltz (Malden, MA: Rowman and Littlefield, 2004), 102–18; Bob Gourley, "Towards a Cyber Deterrent" (working paper, Cyber Conflict Studies Association, Vienna, VA, 29 May 2008), http://www.ctovision.com/cyber-deterrence-initiative.html; Thomas P. M. Barnett, "Deterrence in the 21st Century," in *Deterrence 2.0: Deterring Violent Non-State Actors in Cyberspace*, ed. Carl Hunt and Nancy Chesser (Washington, DC: US Strategic Command Global Innovation and Strategy Center, 10 January 2008), 25–31; Edward D. Mansfield, *Power Trade and War* (Princeton, NJ: Princeton University Press, 1994); John J. Mearsheimer, *Conventional Deterrence* (Ithaca, NY: Cornell University Press, 1985); Jack S. Levy, "The Causes of War: A Review of Theories," in *Behavior, Society and Nuclear War*, vol. 1, edd. Philip E. Tetlock et al. (New York: Oxford University Press, 1989), 209–333; A. F. K. Organski and Jacek Kugler, *The War Ledger* (Chicago: University of Chicago Press, 1980); Michael W. Doyle and Stephen Macedo, *Striking First: Preemption and Prevention in International Conflict* (Princeton, NJ: Princeton University Press, 2008); T. V. Paul, Patrick M. Morgan, and James J. Wirtz, eds., *Complex Deterrence* (Chicago: University of Chicago Press, 2009); and Anthony C. Cain, ed., *Deterrence in the Twenty-First Century: Proceedings* (Maxwell AFB, AL: Air University Press, 2010).

45. Treaty between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missile Systems, US-USSR, 26 May 1972, accessed 13 June 2016, http://www.state.gov/t/isn/trty/16332.htm.

46. Mearsheimer, *Conventional Deterrence*, 23

47. This calculus can be traced to Thucydides, who lamented in the fifth book of his *History of the Peloponnesian War* that in war "one side thinks that the profits to be won outweigh the risks to be incurred, and the other side is ready to face danger rather than accept an immediate loss." Cited in Athanassios G. Platias and Constantinos Koliopoulos, *Thucydides on Strategy: Grand Strategies in the Peloponnesian War and Their Relevance Today* (New York: Columbia University Press, 2010), 125.

48. Harold H. Kelly, "The Process of Causal Attribution," *American Psychology* 28, no. 2 (1973): 107–28; Amos Tversky and Daniel Kahneman, "Judgment under Uncertainty: Heuristics and Biases," *Science* 185, no. 4157 (27 September 1974): 1124–31; and Rich-

ard Nisbett and Lee Ross, *Human Interference: Strategies and Shortcomings of Social Judgment* (Englewood Cliffs, NJ: Prentice Hall, 1980).

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51. Norman Dalkey and Olaf Helmer, *An Experimental Application of the Delphi Method to the Use of Experts* (Santa Monica, CA: RAND, July 1962); and Harold A. Linstone and Murray Turoff, eds., *The Delphi Method: Techniques and Applications* (University Heights: New Jersey Institute of Technology, 2002).

52. William D. Rogers, "The Principles of Force, the Force of Principles," in *Right v. Might: International Law and the Use of Force*, ed. Louis Henkin et al. (New York: Council on Foreign Relations, 1991), 95–108.

53. This type of thinking can also be found in Ali Karami, "Pandemics and Its Consequences for the Future of Asia," in *Imagining Asia in 2030: Trends, Scenarios and Alternatives*, ed. Ajey Lele and Namrata Goswami (New Delhi, India: Academic Foundation Press, 2011), 153–65; and Angela Woodward, "Biological and Chemical Terrorism," in *Imagining Asia in 2030: Trends, Scenarios and Alternatives*, ed. Ajey Lele and Namrata Goswami (New Delhi, India: Academic Foundation Press, 2011), 323–35.

54. "Wayback Machine," *Internet Archive* (web site), n.d., accessed 24 April 2012, http://archive.org/web/web.php.

55. Peter Ho and Adiran W. J. Kuah, "Governing for the Future: What Governments Can Do," *Prism* 5, no. 1 (2014): 8–21.

56. See Risk Assessment and Horizon Scanning (RAHS) Programme Office, Government of Singapore, "About Us: Vision, Mission & Values," 13 January 2012, accessed 24 April 2012, http://app.rahs.gov.sg/public/www/content.aspx?sid=2951; and RAHS Programme Office, Government of Singapore, "Organisation Structure Website," 30 March 2012, accessed 13 June 2016, http://app.rahs.gov.sg/public/www/home.aspx.

57. John P. Geis II, Grant T. Hammond, Ted C. Hailes, and Harry Foster, "Blue Horizons III: The Age of Surprise" (unpublished briefing given to AF/A8, April 2010).

Additive Manufacturing
From Form to Function

Amanda M. Schrand

We might possess every technological resource . . . but if our language is inadequate, our vision remains formless, our thinking and feeling are still running in the old cycles, our process may be "revolutionary" but not transformative.

—Adrienne Rich, poet

Abstract

This article explores the status and opportunity space of additive manufacturing (AM) for defense efforts, while explaining its shaping for multidomain (land, air, maritime, space, and cyberspace) applications through strategic and operational agility. As an efficient tool for design reiteration and rapid prototyping, AM is changing the landscape of the US manufacturing base. Technological advances in the private sector are being implemented into national defense efforts, including investment in a National Network for Manufacturing Innovation (NNMI). However, for AM to be considered a "game changing technology," increases in functionality of the fundamental building-block materials and printer configurations are needed to enable the most revolutionary applications. Simply put, the vision is to move additive manufacturing technology from form to function. In this way, AM can be increasingly used in military mission areas such as logistics, sustainment, and modular weapons development.

* * * * *

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The concept of strategic agility is defined by the attributes of flexibility, adaptability, and speed, thereby providing an answer to the challenge of rapid, unexpected change.[1] Similarly, operational agility—defined by the rapid generation of solutions and the ability to shift among multiple solutions for a given challenge—provides an answer to emerging threats.[2] AM fits into plans for both strategic and operational agility.[3] It is a potential game-changing technology that can maximize multidomain (land, air, maritime, space, and cyberspace) integration, which provides great flexibility.[4] The reality is that the defense challenges of the twenty-first century cannot be resolved with a single answer but require agility to offer many answers. The rapid pace of change can clearly be seen as an impediment to those unable to adapt, but it also becomes an enduring advantage to the agile.[5] While we may not always need to operate at the fastest speed possible, the option to do so reduces an adversary's opportunity to react.[6] AM enables agility by providing fast and inexpensive design and the manufacture of single or multiple prototypes to meet a range of mission needs, including instant part repair and replacement in the field.[7] The ability to place printers and materials in various strategic locations—including land, sea, and space—provides options for on-demand product production to reduce manufacturing cycle times in the design and assembly phases. There is a strong case that AM holds the potential to support many facets of the US defense mission while providing long-term cost savings.[8]

The goal of this article is to provide an awareness and perspective for future joint efforts by exploring the status and shaping of AM capabilities through the strategic framework contained within key US Air Force (USAF) reports, planning documents, and other relevant resources. While this effort focuses on USAF examples, the concept of AM can apply to all Department of Defense (DOD) services and agencies. The article begins by exploring the growth of AM within the military and then ventures into the role of AM in logistics and sustainment. Next, it assesses the impact of AM on the acquisition process and concludes with future opportunities and challenges of AM.

Growth of AM in the Military

The United States is undergoing an intense reinvigoration of its industrial manufacturing base to harness the effective design reiteration and rapid prototyping capabilities afforded by AM. For example, according to the *Wohlers Report 2015*, the AM industry has seen tremendous growth since 1995 when it was a $295 million endeavor to a projected $4.1 billion market in 2014. The number of industrial 3D printer manufacturers has more than tripled since 1995 when there were only 15. There are now 49 companies in 13 countries, selling more than 12,850 systems valued from $5,000 to upwards of $500,000 each. The dominant industrial sectors that utilize AM in order of greatest to least include industrial/business machines (17.5 percent), consumer products/electronics (16.6 percent), motor vehicles (16.1 percent), aerospace (14.8 percent), medical/dental (13.1 percent), academic institutions (8.2 percent), government/military (6.6 percent), "other" such as oil, gas, and commercial products (3.9 percent), and architectural (3.2 percent). Although the percentage for government/military use of AM is summarized as only 6.6 percent, according to the *Wohlers Report 2015*, this is a 1.2 percent growth from the previous data in 2014.[9]

Each of the military branches, as well as most of the depots and arsenals, are conducting independent AM development efforts and projects.[10] For example, 3D printers have been deployed into "the field" by the Army, Navy, and DOD contractors from 2012–2014 and continue to be incorporated into new exploratory efforts.[11] There are also significant collaborations across the services, all of which have been initiated or strengthened in the past two years as investments continue to grow.

AM Research and Development for Military Applications

For multidomain effects to be realized, the Air Force Research Laboratory (AFRL) Munitions Directorate at Eglin AFB, Florida, is working in close collaboration with the Materials and Manufacturing Directorate and Sensors Directorate at Wright Patterson AFB, Ohio, to adapt AM into applications such as flexible, modular weapons for limited bay space, changing targets, conformal information systems research, and flexible electronics. The maturation of AM in these target areas will fuel capabilities to increase the lethality of small weapons and decrease the time and cost it takes to refresh critical components.[12]

The Flexible Electronics and General Ordnance Manufacturing (FLEGOMAN) program took a holistic approach to develop AM for multiple parts and materials incorporated into a representative munition, including metallic casings, novel conductive "inks" for electronic traces and capacitors, and modified energetic material formulations compatible with printing. Some of the benefits of directly printing electronics include using space more efficiently than conventionally-made electronics and generating less waste. For example, simplifying electronics into printed patterns on the interior or exterior of weapon systems could allow size and weight reductions and free up valuable internal space. Other examples of printing flexible electronics include radio antennas on soldiers' helmets that could reduce weight and enhance mobility and embedded electronics in clothing that could allow additional protective benefits and health monitoring options.[13]

AM has also enabled proof-of-concept design of subscale penetrators at the Air Force Institute of Technology (AFIT). The novel designs included intricate internal cellular features that are not possible with traditional subtractive manufacturing techniques. A method known as *topology optimization* was incorporated into the design process to generate strategic trusses optimized for stress distribution, which reduces the overall weight of the structure. Further refinements in the metal compositions and post-processing heat treatments to increase strength are under way.[14]

AM detonators have been developed under the FLEGOMAN program in collaboration with the Army's Armament Research, Development and Engineering Center (ARDEC) at Picatinny Arsenal, New Jersey. Indeed, electronic printing is at the forefront of Picatinny Arsenal's research, including inkjet- and screen-printing munitions antennas, fuze elements (such as exploding foil initiators), and batteries.[15] The use of AM techniques has enabled a host of nontraditional, but highly promising, material options to be pursued, including metallic nanoparticles. These novel manufacturing techniques and materials have the potential to surpass the performance of traditionally manufactured devices while enjoying the logistical flexibility afforded by AM.

The Army Aviation and Missile Research Development and Engineering Center (AMRDEC) in Huntsville, Alabama, is developing tools and processes to advance the state of topology optimization for missile structures and components. Topology optimization is a design process used to generate structures that use minimal material to perform a desired function, such as maximized stiffness, tailored natural frequency, and optimized heat flow. The AMRDEC programs will streamline the optimization/design process, improve lightweight cellular structures, incorporate fabrication considerations, and demonstrate optimized missile structures. AMRDEC science and technology programs are in collaboration with Materials Sciences Corporation in Horsham, Pennsylvania; the Sandia National Laboratories; and the University of Pittsburgh. The AMRDEC will stand up a new AM facility in 2017 to accommodate these programs, train AMRDEC personnel, and advance the state of AM for aviation and missile applications.

The Navy has also been taking advantage of the recent surge in AM. As an early adopter, it has used generations of AM technologies for the last 20 years to assist in prototype development. But in the past few years, the Navy has explored AM as a means to overcome the obsolescence of parts. Too often a part produced during the development of a family of ships or submarines is no longer produced by the original manufacturer or the manufacturer no longer exists, leading to costly and long acquisition processes that could leave a ship stuck in port. At the Navy's fleet readiness centers and regional maintenance centers, AM is being used in many different ways to save time and money for the benefit of fleet readiness.[16] As mentioned earlier, the Navy's desire to improve readiness is being tested at sea.[17] To enable AM to produce drop-in parts instead of only prototypes, the Navy's Office of Naval Research has been reaching out to industry. Such partnerships are essential in ensuring that AM-produced parts can meet material and fleet requirements.[18] The Navy weapons' enterprise also seeks to adopt AM as a means of addressing a shrinking American manufacturing base for energetics, to use the uniqueness of AM to improve performance and enhance safety, and to reduce time in getting new energetic systems into the fleet.[19]

AM has not only found terrestrial uses but now resides in space also. The NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama, launched the first 3D printer to the International Space Station (ISS) in September 2014 to test plastics. The second 3D printer was delivered to the ISS in April 2016. In addition to literally printing in space, NASA–MSFC performs reverse engineering based on 3D scanning and AM combined as an integrated manufacturing process to reduce the design-to-manufacture development cycle time. At the NASA Jet Propulsion Laboratory in Pasadena, California a two-dimensional sensor was developed by the Innovative Advanced Concepts program. The sensor is essentially a transparent sheet of plastic with printed electronics that has been proposed to collect environmental data in space or in a planet's atmosphere.

AM in the Logistics and Sustainment Mission

The Air Force sustainment centers located at Tinker AFB, Oklahoma; Robins AFB, Georgia; and Hill AFB, Utah, provide depot maintenance and supply chain operations and management and installation support for the Air Force's most sophisticated weapons systems—from the most advanced aircraft to helicopters. The airpower sustainment mission is ripe for directly applying industry-matured AM capability into nearly every aspect of air logistics operations. However, before delving into specific examples, one must first consider what logistics and sustainment encompass. In a broad sense, *logistics* means having the right thing, at the right place, at the right time and includes procurement, distribution, maintenance, and replacement of materiel and personnel.[20] The DOD definition of *sustainment* includes the provision of logistics and personnel services required to maintain and prolong operations until there is successful mission accomplishment.[21]

In the future, basic logistics runs may be routinely redirected to supply materials to outposts for direct-part manufacturing in the field to meet urgent needs while saving time and money. One such futuristic scenario is captured in the Air Force Future Operating Concept. The goal is to air deliver a container of polymer for directly 3D printing parts at an isolated outpost. The file to print the needed part is sent via a secure space connection, while the airdrop delivery of materials is ultimately successful and the printer generates the critical part within hours compared to days, saving millions of dollars in the process.[22] Scenarios such as this generate great enthusiasm for AM due to the asymmetric advantage it offers national defense. There are many other examples of how AM is envisioned to innovate military logistics, sustainment, acquisitions, and weapons development. Embracing AM into the role of logistics and sustainment creates three opportunities:

- AM can be used to reverse engineer replacement parts for legacy aircraft that are no longer in inventory. Aircraft, such as the venerable B-52 Stratofortress, are aging and often need parts quickly that have not been manufactured for decades. Three-dimensional laser mapping and other techniques can be used to manufacture existing parts.
- Improve the design of existing parts before final parts are manufactured. Dr. Kristian Olivero at the Oklahoma City Air Logistics

Complex said, "Even if your final part is going to be machined, you can print it in plastic five times to make sure it's got the correct geometries, the right tolerances, the correct interfaces, and then machine the final one."[23]

- AM can reduce unnecessary parts purchases and reduce parts inventory by printing replacement parts on demand in the field. However, there is a learning curve to implement and manage this new process into depot maintenance. For example, replacement engine parts are currently purchased, shipped to the depot, stored in inventory, and pulled when needed. Instead, the parts could be printed on demand directly in the field or at repair and overhaul sites, thereby overcoming the need to deploy a range of spare components.[24]

The DOD Additive Manufacturing for Maintenance Operations Working Group (AMMO WG) is a great example of the DOD partnering with industry to:

> …develop an integrated DOD strategic vision and facilitate collaborative tactical implementation of AM technology in support of the DOD's global weapon system maintenance enterprise. The AMMO WG activity includes development of Office of the Secretary of Defense guidance recommendations, selection, and prioritization of opportunities to employ AM technology, coordination, and standardization of AM activities into established DOD maintenance processes and procedures and preparation and maintenance of the AMMO Roadmap.[25]

The National Center for Manufacturing Sciences (NCMS)—a private, nonprofit, technology-development consortium—provides industry leadership and participation from manufacturers across all industry sectors.

The AMRDEC, in collaboration with the Corpus Christi Army Depot, is also working to demonstrate the benefits of laser additive manufacturing technologies for the restoration, reclamation, and reutilization of high-value aviation assets located at the Storage, Analysis, Failure Evaluation, and Reclamation facility.[26] AM will be used to demonstrate repairs on Army aviation assets that cannot currently be restored to service using traditional manufacturing methods. Project objectives include improvement in acquisition lead times for component replacement, reduction in costs that negatively impact operations and support and operational readiness, and the establishment of qualified repair procedures for candidate parts.

Can AM Revolutionize the Acquisition Process?

Reducing the development cycle through highly streamlined and innovative approaches that ultimately accept risk in exchange for acquisition speed can address the mounting concerns about maintaining technical superiority.[27] In the realm of acquisitions, this form of agility could be called *process agility*. Attempts at process agility can be found in *acquisition reform*, where the goal was to merge science and technology and acquisitions and requirements more seamlessly to improve overall capability development. However, this process has not been successful and more recent efforts in the USAF focus on including more "pivot points," or opportunities to change or abandon a program, as well as more rapid prototyping to advance technology through exploring innovative operational concepts.[28] One could envision an acquisitions process reduced to its simplest form through AM by acquiring and fielding the printers, materials, and files responsible for printing vehicles and systems. If successful, this process could revolutionize the speed of the acquisition.

While designing new systems, we must also stay mindful that our adversaries are also modernizing and working to counter our technology, so it must be part of the development process to anticipate and plan for emerging threats.[29] One method to plan for technology insertion is the use of modular architectures, which consist of severable components that can be rapidly upgraded. Additively manufacturing relatively simple autonomous vehicles and systems at lower cost and with modular options presents strategic and operational opportunities for practicing agility in precision global-strike missions in highly contested environments. Many of these assets have incorporated modular platforms—consisting of sensors, decoys, electromagnetic jammers, and munitions—to produce lethal and nonlethal effects.[30] These expendable decoys or small unmanned vehicles provide flexibility by being deployable from any combination of surface, air, or space assets. Modularity also creates the potential for additional providers that could submit products for increased competition and the development of alternative options.[31]

While the purpose for setting up any process is to minimize variation and allow repeatability, sometimes the process becomes so involved we lose sight of the ultimate goal. For example, the qualification and certification process should be reviewed to determine if a more rapid utilization of AM products can be pursued. This could be one small step in eliminating the excessive development times for complex capability systems (15–20 years). A shift in concepts from a "defined and finite" system, or component life, to "adequate," for a certain application and length of time, would also be beneficial for rapid technological advancements.[32] Certification should be approached based on the function and criticality of the AM part. Not all parts will need to undergo a rigorous qualifications process, as many parts could have an acceptable level of risk for the benefit of agility that AM brings. Similar to the benefits of modularity, the rapid fielding of additively manufactured, attritable, unmanned aerial vehicles (UAV) has the potential to reduce development time and save money while implementing new technology. Another example of incorporating AM for rapidly fielded technology is to reduce launch costs, which are currently a major factor facing USAF Space Command.[33]

It is worth mentioning the importance of having a strong linkage to early research and development discoveries while systems are being developed. Without this knowledge through connections to basic research, some technology insertion opportunities may be missed. However, with an awareness of the maturation of individual technologies, we can plan for periodic technology refresh in our acquisition plans while development is still in progress.[34] The lessons learned to date indicate that the US government needs to secure technical control and ownership of the relevant interfaces, including those required for software integration.[35]

A National Manufacturing Network

The incorporation of AM into defense is occurring in parallel with the establishment of a NNMI, originally proposed in 2012 by Pres. Barack Obama via a $1 billion addition to his fiscal year (FY) 2013 budget.[36] The vision for the NNMI is to set up a total of 15 institutes by FY 2024—shared between the government departments, including the DOD, Department of Energy (DOE), Department of Commerce (DOC), and the Department of Agriculture (DOA). As of 2015, a total of eight Institutes for Manufacturing Innovation have been established (five DOD and three DOE). The DOD institutes include the Additive Manufacturing Institute, also known as "American Makes," in Youngstown, Ohio; the Digital Manufacturing and Design Innovation Institute in Chicago, Illinois; the Lightweight and Modern Metals Institute, also known as Lightweight Innovations for Tomorrow, in Detroit, Michigan; the Institute for Integrated Photonics Manufacturing, also known as the American Institute for Manufacturing Integrated Photonics, in Rochester, New York; and the Flexible Hybrid Electronics Manufacturing Innovative Institute, also known as NextFlex, in San Jose, California.

The DOE's institutes are referred to as Clean Energy Manufacturing Innovative Institutes and include the Next Generation Power Electronics Manufacturing Innovative Institute, also known as "Power America," in Raleigh, North Carolina; the Advanced Composites and Structures Materials Manufacturing Institute, also known as the Institute for Advanced Composites Manufacturing Innovation, in Knoxville, Tennessee; and the Clean Energy/Smart Manufacturing Innovative Institute in Los Angeles, California.[37]

Seven new institutes were proposed for 2016 (one for the DOD, two for the DOE, two for the DOC, and two for the DOA)—worth a cumulative total of $608 million. The 2016 DOD-funded institute is the Revolutionary Fibers and Textiles Manufacturing Innovation Institute in Cambridge, Massachusetts. The DOE sought $241 million in 2016 to sustain its four existing institutes and set up two new institutes. The DOA requested $80 million to set up two institutes in the areas of advanced biomanufacturing and nanocellulosics. The DOC's National Institute of Standards and Technology requested the creation of up to two institutes in 2016, based upon any manufacturing topic area not previously selected.

The great diversity of research and development being performed by the National Manufacturing Innovative Institutes is influenced, in part, by military needs. The institutes are set up through both government funding and advisory committees consisting of academic, government, and industry members. For example, the AFRL feeds into the institutes by being engaged in the program reviews and technical working groups and through agency-directed projects.

Future Opportunities and Challenges

The majority of printed parts still rely on the deposition of materials layer by layer to generate 3D structures. However, new technologies and sectors of usage continue to emerge. The future of AM will surely witness an increase in available options, ranging from large companies offering high-throughput industrial printers to small start-ups demonstrating unique capabilities in niche applications. In 2016, the top extrusion and selective laser-sintering printer manufacturers, Stratasys and 3D

Systems, are competing with new computer-aided printing technology introduced by HP (multi jet fusion) and Carbon3D continuous liquid interface production. The main advantages of the new technologies include 10–100x faster print times compared to existing printers and improved surface finishes. The starting materials also play an integral role in overall improvements to product quality. Although acrylonitrile-butadiene-styrene (ABS) and polylactic acid (PLA) plastic filaments are still extensively used by many printers, the list of available materials is steadily growing, including custom-designed composites, glass, ceramics, and conductive inks. The implementation of AM is fostered by increased competition between emerging printer companies and material providers, but the cost of materials is still a concern for the mass adoption of AM. There are some discussions of using indigenous resources and assets such as recycled materials, especially for printing in remote locations where material delivery could be problematic.[38] Natural resources such as sands, clays, organic debris, and harvestable marine materials are also being considered as material options.[39]

The size of printed structures continuous to grow, including low-cost modular buildings in China, Italy, and here in the United States. The tailorable layer-by-layer construction of such large structures has been compared to the millennia old ancient pyramids, which were not only impressive in size but contained intricate internal passageways.[40] Although the size of these structures is quite impressive, for AM to be considered a revolutionary "game-changing technology," increases in functionality of the fundamental building block materials and printer configurations are envisioned to enable the most revolutionary military applications. Some initial work has demonstrated pick and place sensors into printed structures to "embed" functionality, which is one step toward more-advanced 3D printed devices. The materials to enable thermal and electrical conductivity for electronics (for example, traces, solders, and such) also are undergoing rapid development, taking advantage of the unique properties of nanoconstituents such as silver and carbon nanotubes. The formulation development has resulted in "inks" that exhibit shear thinning and are thereby suitable for the many commercially available 3D printers that use syringe-style printing as well as adaptations of commercial printers with multiple printheads for multimaterials printing.[41] These are important developments toward functional products that consist of several different materials deposited by a single system.

Government entities have a role in tech "push" to influence the direction of commercial innovations. Some examples of possible next-generation manufacturing technologies geared toward multidomain national defense strategies could include optimized 3D printing and embedding of electronic components, strain gauges, and other sensors within aerodynamic structures and war fighters' battle gear to monitor the environment, performance, and wear and offer redundancy in forms of communication.[42] Techniques such as topology optimization for seating to better accommodate ergonomics of female pilots could be based upon 3D printed seat prototypes, leading to more comfort and reduced accidents.[43] The seats, helmets, and other equipment could even be tailored to the individual to create a truly customized flight environment. With the advent of advanced materials and printer systems, we can also expect to see an increase in fully printed UAVs and robots that perform dangerous tasks.[44] Growth in the area of additively manufactured textiles lends itself to smart fabrics for biomonitoring in the military as well as alternatives to meal replacements through printing tailorable nutrition. The large-scale printing of structures, especially with indigenous materials, lends itself to applications in disaster relief and the rapid setup of military camps.

There remains the challenge of generating original 3D-printing designs from software that has traditionally been used for subtractive manufacturing. However, many companies are working to generate software that is truly additive in nature, starting from a blank slate versus a fully populated material block. Along with software development, the actual time required to produce original designs can be a limiting factor for rapid prototyping. One solution is to start from a scanned file of a similar object and then perform modifications. Alternatively, a database containing high resolution files could be accessed based upon a part number or a scanned object. Disney has filed such a patent on "object recognition for 3D printing," which takes advantage of a low-resolution scan to match and print the object from a high-resolution copy contained within a database.[45] If such technologies become widespread, the acquisitions process could be reduced to its simplest form and become much more agile and rapid via AM. For example, printers could be acquired and fielded along with the materials and files responsible for on-demand, in-the-field printing vehicles and systems.

One overarching challenge within government and military efforts is to effectively coordinate AM activities. There are mounting concerns that the highly bureaucratic nature of the national manufacturing institutes and a general lack of awareness and coordination between the entities involved are resulting in a piecemeal approach that duplicates efforts, magnifies costs, and suboptimizes the eventual benefits of AM.[46] As a remedy, a reorganization effort is proposed in the form of a disciplined but flexible governance structure for all AM activity, such as centralized AM leaders in the government departments whose role includes coordinating AM strategy and policy and issuing guidance to all departmental organizations planning to implement AM—from line units in the field to sustainment centers around the globe.[47] A specific suggestion to lead the reform and strategic vision from the Office of the Secretary of Defense—specifically the Office of Emerging Capability and Prototyping—has been offered as a solution.[48] Therefore, for any real forward momentum to occur, the push to reform the present structure of AM efforts to a more forward-thinking posture will need to occur in parallel with technological innovation.[49] Beyond capturing and furthering the vision presented in the high-level strategic USAF documents presented in this article, there is a real need for leaders to be able to cut through the hype and present the critical gaps and technical challenges to closing those gaps. What are the challenges currently being faced at the depot level for implementing AM? Additionally, what are the near-term payoffs in military applications compared to progress in the AM community as a whole?

Conclusion

To expand military strategic engagement in AM, the synergy between the diverse arrays of available materials, evolving printer technologies, and established programs—including the NNMI—should be leveraged to accomplish the vision set forth for long-term enterprise efforts. The goal of moving AM from form to function is already being demonstrated in efforts increasing functionality (for example, embedded sensors) with materials development—such as thermal/conductive inks—and more sophisticated printing capabilities like multimaterial printing. Using AM in ways that maximize strategic and operational agility provides decision makers with viable solutions for the multidomain challenges facing our country.[50] Incorporating AM has broad implications for logistics and sustainment due to its ability to rapidly field capabilities. The time and cost savings afforded by AM have the potential to revolutionize acquisitions and redefine system qualifications and certifications. Therefore, the opportunity to apply AM to increase the agility of the diverse, multidomain, defense mission set is one step in ensuring that the United States has the dominant capabilities to meet emerging national security threats. SSQ

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DARPA Emerging Technologies

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Abstract

Current research at the Defense Advanced Research Projects Agency (DARPA) investigates the realm of the possible and provides insight into future force structures. DARPA is pursuing critical breakthrough technologies to enable a dispersion of assets while maintaining concentrated effects. In particular, this article presents breakthrough research in disaggregated capabilities, hypersonic strike weapons, and directed energy. These capabilities will be essential for operations in anti-access/area-denial (A2/AD) regions and offer to replace the monolithic manned platforms with a network of integrated systems disaggregated across teams of manned and unmanned air vehicles. Coupled with hypersonic standoff-strike munitions and enhanced directed-energy capabilities, these technologies provide a viable option for maintaining a credible global strike capability.

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Maintaining a strong military pillar of national power by providing a credible ability to hold adversaries at risk while protecting US interests is vitally important to achieve national strategic objectives. In most conceivable future conflicts, the only certainty is the existence of complex threats. Some of the emerging technologies currently in development at DARPA can mitigate these threats.

DARPA's mission is to make pivotal investments in breakthrough technologies for national security. Toward that end, the agency has focused on critical technological areas and developed a vision of what may be required to remain viable against emerging threats. The design space in which DARPA operates is quite vast. As an aspirational aphorism,

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DARPA quotes Franz Liszt, who intoned the following raison d'être, "To cast a javelin into the infinite spaces of the future." To ensure a less than infinite scope, this article will focus on three areas that are most critical in the air domain against complex, layered integrated air defense systems. This environment is part of the more broadly described concept of anti-access/area-denial (A2/AD) and provides a defining system stressing strategic challenge for future force structures. Of the many mission areas that could be explored to provide access to A2/AD environments, three seem particularly promising:

1. saturating the A2/AD environment with multitudes of low-cost, networked vehicles that provide disaggregated capabilities;
2. staying outside the denied area and systematically rolling back enemy air defenses by launching standoff weapons that are very high speed (hypersonic), maneuverable, and reasonably survivable against projected defenses; and
3. pursuing advancements in high-energy lasers that provide defensive and offensive technologies enhancing platform survivability while imposing costs on the adversary.

A successful combined arms strategy contains elements of each of these areas.[1] Even if these capabilities are never exercised, the investment bolsters the US ability to influence international affairs. Indeed, a truly successful national defense strategy achieves its ends without ever firing a shot. Examining progress in these areas influences technology to provide material solutions to proliferating geopolitical challenges. Only through consistent investment and persistent effort will developments in disaggregated network capabilities, hypersonic strike vehicles, and directed energy provide a credible capability to hold adversaries at risk, bolstering the military pillar of national power and protecting future American strategic interests.[2]

Disaggregated Capabilities

Using technological superiority to protect human life is a hallmark of US military culture. As a result, the trend in Air Force acquisitions has been toward ever more expensive manned platforms that have increased in size and complexity to address the increasing demands of the modern battlespace. In light of finite resources, the increased unit costs of these large capital assets have led to a corresponding decrease in quantity. Today, in light of constrained budgets, rising economic near-peer states and global uncertainty that demands agility, this trend is unsustainable. Since quantity is a key enabler of geographic flexibility, providing quantity at a reasonable price requires a radical shift in this single platform based allocation of resources.

As early as 1982, aerospace businessman Norman Augustine identified a trend in defense acquisition that showed that defense budgets grow linearly, but the unit cost of new military aircraft is growing exponentially. Augustine humorously quipped, "In the year 2054, the entire defense budget will purchase just one tactical aircraft. This aircraft will have to be shared by the Air Force and Navy 3½ days each per week except for leap year, when it will be made available to the Marines for the extra day."[3] This very real trend limits operational flexibility, since small numbers of aircraft cannot be in multiple locations at the same time. Furthermore, antiaircraft defenses are becoming so advanced that spending more to produce the most effective strike aircraft does not reasonably ensure its survival. With these pressures in mind, a paradigm shift is necessary. This shift is sometimes described as the third offset strategy. Deputy Secretary of Defense Robert Work clarified five key building blocks for the third offset strategy in policy speeches in late 2015.[4] These building blocks are as follows:

1. autonomous machine learning,
2. human-machine collaboration,
3. assisted human operations,
4. advanced human-machine combat teaming, and
5. network-enabled, cyber-hardened, semiautonomous capabilities.

Putting these building blocks together in the air domain leads to a new system-based force architecture. In this vision, teams of manned and unmanned systems provide military utility, cost imposition to the adversary, and adaptability through the use of disaggregated network capabilities. Spreading out capabilities across multiple network-linked platforms, rather than concentrating all functions on a single expensive platform, enhances flexibility, scalability, and specialization. As a first step, the term *disaggregated* is appropriate because it shows a clear delineation from legacy monolithic single-platform-based aggregated capabilities. As this concept matures, however, and new capabilities are added to the network that would not have existed on current platforms, *distributed capabilities* is perhaps the more appropriate term. Since this article speaks primarily to the transition period, these terms are used interchangeably. Critical challenges of disaggregated systems include platform development; human-machine interfaces; secure, reliable network communication; and overall system architecture/command and control. Within DARPA this concept is called a system-of-systems approach, and one such concept for disaggregated capabilities is shown in figure 1.

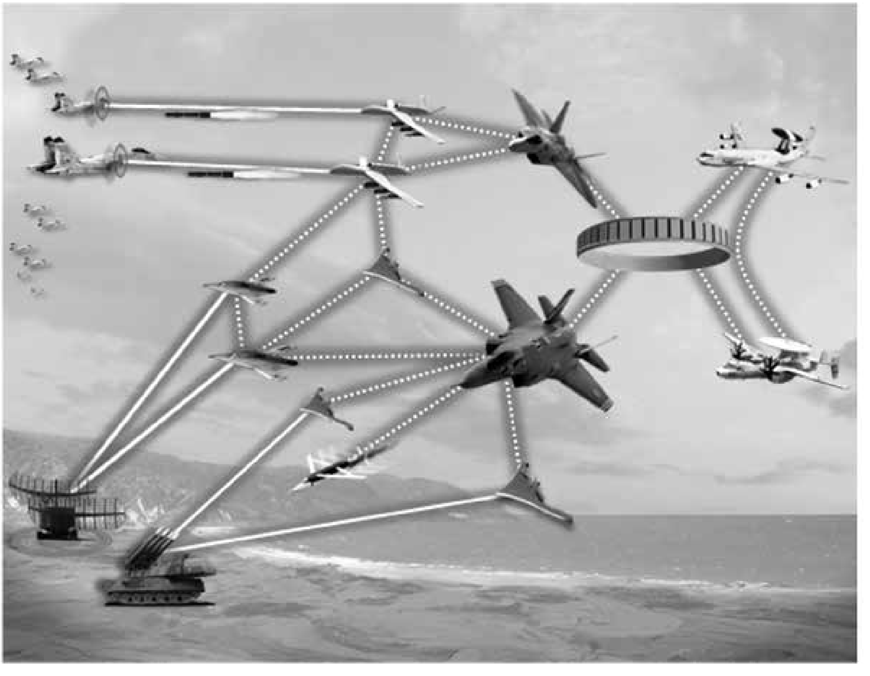

Figure 1. Distributed capabilities. (Image courtesy of DARPA's Strategic Technologies Office.)

The following pages address three current DARPA efforts that seek to leverage advantages of distributed capabilities using the building blocks of the third offset strategy while addressing the critical challenges: (1) the Gremlins program provides low-cost unmanned platforms that are geographically flexible, (2) the Aircrew Labor In-Cockpit Automation System (ALIAS) program lays the groundwork for more effective human-machine collaboration through machine learning and enhanced human-system interfaces (HSI), and (3) the Collaborative Operations in Denied Environments (CODE) program builds the algorithms for human-machine teaming and semiautonomous collaboration.

The Gremlins Program

Building effective systems that do not require a person in the cockpit can help reimagine the cost equation and create less expensive systems in larger quantities. Not only does this address the need for geographic agility but it also provides a viable solution for the challenges of the A2/AD environment. Though these systems may not be able to survive a complex air defense environment individually, in large quantities they may be able to saturate an adversary's engagement capability. Low-cost, attritable unmanned aerial vehicles (UAV) operating in cooperative packs can prosecute complex missions in high-threat environments without putting US pilots at risk. Furthermore, this can be accomplished in a cost-imposing fashion. For example, if a UAV costs less than the missiles required to defend against it, this is a cost imposition on the adversary. The goal, therefore, is to build systems that are lethal enough that they cannot be ignored but inexpensive enough that the loss of an individual vehicle is acceptable. As a new DARPA program, Gremlins is a system of unmanned platforms that seek to avoid the high costs of life support and complex defensive capabilities normally required of manned aircraft.[5]

Figure 2. DARPA Gremlins. (Image courtesy of DARPA's Tactical Technology Office.)

Gremlins are UAVs conceived to be air-launched and air-recoverable in volley quantities. This provides the platforms needed to constitute a cooperative pack of capabilities to prosecute various missions. However, to keep costs low, these vehicles must be relatively small, which means their range is limited. To overcome this challenge, the Gremlins program leverages a larger host aircraft to take the Gremlin fleet to the edge of the contested area before launch. Because the Gremlin air vehicles (GAV) are recoverable rather than expendable; the per-use costs are much lower than for a cruise missile or traditional decoy.[6] Mission success is defined as meeting objectives with a specified percentage or less of the individual munitions or vehicles being destroyed along the way.

GAVs could be launched from a wide array of aircraft, including bombers, fighters, and cargo aircraft. A notional approach, and the flight demo planned for the Gremlins program, leverages air recovery into an aircraft with a cargo bay. The most challenging technical risk of this project is solving the problem of air recovery without endangering the host. GAV air recovery is still in development, but designs focus on three critical capture phases:

1. soft capture outside of the highly turbulent region directly aft of the host aircraft using precision navigation techniques demonstrated through previous UAV air-refueling programs;
2. hard capture into a structure that provide six degrees of freedom restraint for transition through the turbulent region aft of the host. This phase leverages advances in robotics. Of note in this phase, GAV aerodynamic surfaces will retract, and the engine will be shut off and inserted to protect the host aircraft; and
3. transition into the cargo bay and automated rack storage of volley quantities of GAVs.

The demonstration goal is to recover four vehicles every 30 minutes. Once air recovery is successfully demonstrated, various air vehicles could be developed to address specific mission needs. The Gremlins' objective system is roughly the size of a cruise missile and has the following design goals shown in table 1.

GAVs are large enough to carry relevant electro-optical sensors for intelligence, surveillance, and reconnaissance (ISR) and for target identification, with enough onboard power for electronic attack. As needed, they could carry a warhead with enough destructive power to engage semihardened targets.

Table 1: Gremlins air vehicle key performance parameters

	Threshold	Goal
Design radius	300 nm	500nm
Design loiter time at design radius	1 hr	3 hr
Design payload	60 lb	120 lb
Maximum one-way range, no loiter	Fallout from system design	
Loiter time for recovery	As needed	
Maximum speed	Mach 0.7	Mach 0.8+
Max launch altitude	not specified	40,000 ft + (compatible with launch from many aircraft
Propulsion system	Objective system may be designed with conceptual design engine model (at existing technology level), or existing propulsion system, or modified propulsion system (e.g., addition of fan stage).	
Payload power	800 Watt	1200 Watt
Payload installation	not specified	Side and fore/down-facing aperture provisions
Payload type	Modular, with provisions for depot-level change–out among various payloads, including radio-frequency (RF) payloads and electro-optical infrared (EO/IR) payloads, among others. Assume typical RF payload power density to determine payload size/volume requirements.	
Design life	not specified	20 uses
Gremlin air vehicle recurring (flyaway) cost, exclusive of mission payloads	$700 K (FY15)	Minimal cost
Gremlin system-level metrics		
Host launch platforms	B-52, B-1, C-130	As many aircraft as possible, including tactical (fighter)
Launch quantity	8 or more per host	20+ for large aircraft host
Host recovery aircraft	C-130	
Recovery quantity and timeline	≥4 Gremlins recovering in <30 min; goal to be capable of recovering 8 or more in total.	
Probability of successful recovery	≥0.95 within time window	
Probability of host (launch or recovery) aircraft loss due to gremlins operations	not specified	<1x10^-7 incidents per flying hour
Recovery and refurbishment cycle	<24 hours from recovery to refit onto aircraft for launch, with minimal manpower and personnel costs. Fit within USAF structure for maintenance/checkout at forward operating base.	
Host system equipment, recurring (flyaway) cost, exclusive of command/control system costs.	$10 M (FY15)	$2 M or less (FY15)

Payload and power requirements were set by a number of other DARPA programs, ranging from coherent jamming to advanced cooperative synthetic aperture radar mapping to electronic attack with cyber effects. For many of these radio frequency–domain effects, speed is a key enabler. At Mach 0.7+ the objective system is fast relative to existing UAVs, enabling flexibility in payload employment. High speed also allows the vehicles to potentially team with other strike assets or fly ahead of special operations infiltration/exfiltration teams. Survivability is also enhanced by speed and altitude capabilities that remove the vehicle from traditional small arms and man-portable surface-to-air missile weapons engagement zones. Small size naturally enhances low observable characteristics, and this will be a design consideration for future weapons systems.

Air launch and recovery directly addresses several critical challenges of global agility. First, it offers global access and rapid response. The US military currently enjoys freedom of movement throughout most of the world's airspace. With existing global mobility assets, Gremlins launching from bases within the continental United States (CONUS) could be employed anywhere in the world within 36 hours. Corollary to this is no dependence on vicinity basing. Current UAVs are slow and require significant infrastructure directly in the region of interest. This is unrealistic in emergent scenarios in regions where we have little forward basing or in A2/AD environments where we may not have land or sea control close to our objectives. Air recovery offers fast cycle time. The vehicles may be refueled, serviced, and ready to fly again quite rapidly.

GAVs offer a compelling solution to the platform challenge in creating disaggregated capabilities. Air launch and recovery of sophisticated unmanned assets enables scalability and diverse effects in a fiscally efficient manner. Though the focus here is on saturation-layered defenses as the most challenging use case, disaggregated network-based capabilities also allow a more efficient use of resources across the spectrum of conflict. When relying on platform quality rather than quantity, that expensive platform is underutilized when employed in less-demanding environments. For example, using a B-2 to strike an undefended adversary's pickup truck is certainly fiscally inefficient. Disaggregated low-cost platforms use quantity to scale to the requirements of the scenario. In the most demanding case, more platforms saturate defenses. In less challenging scenarios, fewer platforms can be employed. In this way, capabilities utilization is better matched to mission requirements. When facing economically near-peer adversaries, cost efficiency is a necessary strategic consideration.

Platform development is only one piece of the challenge in creating disaggregated capabilities. Also critical is effectively interfacing with the human mind directing these assets. Toward that end, DARPA is pushing the realm of the possible in human-machine collaboration and machine learning through the ALIAS program.

Aircrew Labor In-Cockpit Automation System

ALIAS seeks to develop and insert new automation into existing aircraft to increase mission effectiveness and safety while enabling operations with reduced onboard crew.[7] To achieve this goal, the program is dramatically pushing the frontiers of machine-learning capabilities and developing robust methods for human-machine collaboration. The system is designed to be quickly transferable from vehicle to vehicle, requiring rapid knowledge application and flexible implementation. As such, the core problem-solving algorithms being developed to meet this program's requirements will likely have broad applicability in autonomous and semiautonomous operations. The way a future operator will interface with the cooperative packs will likely be a derivative of this program. The way future vehicles solve mission challenges with a man in the loop or autonomously will likely be based on the ALIAS computational core. This is a whole new realm of possibility, and ALIAS is an important first step.

The heart of the ALIAS program is the intelligent processing core that provides flight management and system analysis. Information is fed to the system through a knowledge acquisition system that uses real language processing to digest normal text and subdivide it into a logical framework that can be queried by the core. In this way, the machine can quickly acquire all printed knowledge on a topic and learn the exact procedures for conducting myriad flight maneuvers. The system also can be taught by an expert human demonstrator and will internalize that lesson. Data quality will be prioritized, and a human subject-matter expert can resolve discrepancies. The ability to rapidly acquire and codify diverse data sets is truly revolutionary and has application far beyond the scope of this program. One can imagine using the process devised through this program to streamline ISR data analysis or develop real-time command-and-control suggestions based on application of operational doctrine. Within the scope of the current program, the system will provide robust analysis of mission and flight contingencies. The

ALIAS system can analyze options and provide aircrews with feedback on mission impacts. In this way, the crew acts as a mission coordinator focused on high-level execution—rather than being technicians. In addition, the core will be able to deal with system contingencies such as an engine failure. It would pull up appropriate checklists, possibly actuate switches, and define mission impacts, providing the crew with options.

The ALIAS program is also developing a perception system. ALIAS is intended to be an ultimate state machine—a machine that can simulate any computer algorithm, no matter how complicated—that measures and monitors all critical mission elements like airspeed, altitude, fuel state, location, subsystem status, mission intent, and vehicle performance. This can be done through internal cameras reading gauges and dials and switch positions, directly tapping into current or future avionics service buses and integrating datalink signals or external cameras.

A revolutionary step this program is taking is including the human operator as a parameter in the human-machine state. To this end, cameras may be used to track pilot posture and reactions, control actuation could be measured to gauge pilot attentiveness, and, in one intriguing application, pilot brain waves could be directly monitored in flight using electroencephalography (EEG) sensors integrated into the pilot's headset or helmet. This concept builds on the work from a DARPA-funded effort entitled BrainFlight, which used active brain monitoring in flight to measure workload and predict pilot-induced oscillations. Building on a host of successful brain-monitoring programs brings enormous potential to more directly interface the human brain with machines. Employing EEG as an input to the ALIAS perception system is an exciting step toward tapping into that potential. At a minimum, monitoring the pilot's performance will give the system key information allowing it to recognize if the human is fatigued or overloaded or missed an alert. As a result, there may be more effective two-way communication between the ALIAS system and the human operator.

Finally, the ALIAS system eventually will be able to fly aircraft, move switches, and perform operations just as a human could. Because the system is intended to be portable from aircraft to aircraft, actuation concepts are typically kit-based with slightly different implementations based on the constraints of the aircraft involved. The kit could consist of various mechanical switch actuators, robotic elements, direct mechanical linkages to flight controls, direct electrical interfaces into the buses, or other similar devices. No single actuation system will work in all aircraft; thus, a suite of solutions will be available. Notably, flight control applications are being built with the high level of reliability and redundancy one would see in a digital flight-control system. Unlike a typical autopilot that is built with single path failure modes that require the human to take over in contingency situations, the ALIAS flight-control actuators are triple redundant, providing extremely high reliability. Beyond being just a better autopilot, ALIAS could prove to be at least as reliable as a human operator, enabling a major technical leap forward.

ALIAS is addressing head-on the somewhat nebulous concept of human-machine teaming. Typical pilot/copilot functions are not directly transferable to an optimal human-machine team. Humans excel at certain functions, such as applying tactics and building strategy, and machines transcend in other realms, such as routine station keeping and rapid computation. ALIAS provides a platform to redefine typical crew roles to provide an even more effective team. Furthermore, ALIAS may enable human operators to work outside their own cockpit. As operating their own vehicle is simplified, they could have capacity to cooperatively direct other vehicles. In the future, humans may work alongside unmanned semiautonomous wingmen and strike vehicles. Working with these disaggregated assets requires algorithms that translate human intent into coordinated semiautonomous action. This is made even more difficult since future wars may likely be fought in radio-frequency and GPS-contested environments. Human-machine teaming and semiautonomous collaboration in contested environments are critical capabilities and are central concepts in DARPA's Collaborative Operations in Denied Environments (CODE) program.

Collaborative Operations in Denied Environments

CODE seeks to develop advanced autonomy algorithms and supervisory control techniques to enhance the capability of UAVs or sophisticated missiles in denied environments.[8] This is addressed through four major technical areas: (1) collaborative autonomy, (2) vehicle-level autonomy, (3) supervisory interface, and (4) open architecture for distributed systems. Key technological advancements focus on autonomous collaboration for sensing, strike, communication, and navigation, reducing required communication bandwidth and HSI. These goals are being pursued through simulations and software development currently and aim to culminate in a large flight demo using live and virtual assets in a GPS- and communications-denied environment.

Collaborative autonomy is a somewhat vague term, but perhaps some specific examples will clarify its meaning. Imagine a dozen cruise missiles deep in enemy territory looking for a mobile surface-to-air missile (SAM) site. One could assign each missile independently a search/kill box and hope to find and destroy the SAM in this way. Using collaboration instead, the cruise missile pack could set up a coordinated search grid, notify other missiles of targets of interest, and bring multiple sensors and azimuths to bear to increase the probability of accurate target identification. Adding to this scenario, assume GPS is not available—removing a trusted outside navigational source. This makes accurate positioning and targeting difficult. Within a collaborative network, relative position can be determined. Using known landmarks or a single navigational beacon, the entire pack of missiles can update their position. In this example, absolute position is not that important. Known relative position to the target is sufficient to close the kill chain. Once a target is identified, the cruise missiles could encircle the target and strike simultaneously, overwhelming any missile defense systems in place. Collaboration allows for greatly increased effectiveness and efficiency, allowing the salvo size to be reduced. This effects-based thinking preserves resources while optimizing mission success.

Another important aspect of collaboration is coherent radio-frequency effects. Multiple platforms with very accurate clocks can transmit waveforms that combine constructively. It turns out that combining waveforms in this way actually scales via a square of the number of platforms rather than just being additive. Hence, coherently combining signals from four collaborative platforms can provide up to 16 times the broadcast power. Coherently combining even larger numbers of signals can be immensely powerful, yielding significant increases in detection and communication range or enabling burn through of enemy jamming.

Efficient use of available bandwidth is vital to collaboration in a challenging RF environment. The objective is to maintain a common situational awareness picture across the team. This is done by decreasing the information each vehicle needs to know about the state of other vehicles through behavior and health modeling. For example, rather than sending constant updates on how much fuel a vehicle has on board, each member of the team can calculate how much fuel it expects its team members to have based on an internal model. Therefore, updates to fuel status could be very infrequent or only happen when actual fuel levels diverge from model expectations. Information that must be passed is assigned a value and is compressed based on what is important for that specific mission engagement. Early studies show this to be extremely effective over time, reducing the bandwidth required by a factor of 20.

Large numbers of semiautonomous vehicles under the control of a human mission commander demand a new vision for the HSI. The core challenge is interacting with dozens of UAVs in intermittently denied communications environments. Even under high workload, the human operator must be able to maintain situational awareness. High-functioning autonomy must be employed in an informed manner without sacrificing appropriate human oversight and control. At the same time, autonomous vehicles must react reliably and consistently, building operator trust. On the spectrum of human to remote vehicle control, one extreme would be the General Atomics MQ-1 Predator UAV, where a human pilot directly controls all flight functions. A more viable model for the future is applying the notion of commander's intent. Packs of UAVs could be sent out with clearly defined objectives and prosecute that mission autonomously even if severed from communication with the mission commander. In accordance with the rules of engagement, the commander would be notified before predefined actions were authorized, such as a weapon's release or crossing a geographic border. At the same time, relevant data should be presented to the human mission commander so he or she can make reasoned decisions. Porting raw data from so many sensors back to the human would be overwhelming. Instead, specific actionable information that shows behavior over time and mission relevant trends builds optimal situational awareness. There is a rich heritage of command and control using dispersed human teams. This can serve as a starting point for developing human-machine teams. However, ultimately the allocation of labor should leverage inherent human and machine strengths rather than blindly following old models of behavior simply because they are familiar. CODE is exploring a suite of mission planning tools and interfaces to overcome these challenges and provide the right level of information to humans, allowing them to exert the right level of control over the machines. Figuring out this "Goldilocks" zone is a major thrust of the program's research.

Open-system architecture is critical to development of the CODE communication backbone. Legacy systems and new designs not yet built must be able to operate together in an environment that allows for continuous improvement. This is enabled by providing all players with clearly defined, government-owned interfaces allowing rapid integration, adaptability, and flexibility in testing. Open architecture is a design commitment that must be built into the system at every step of the way. However, given the goal of allowing collaboration between many different assets, it is essential to the CODE vision.

A host of programs in development aim to support network-based disaggregated capabilities. The programs that enhance overall capabilities but are not critical to the vision should be consistently researched. Predictability in programmatics is the key to efficient design, prototyping, and testing. Sudden surges and crashes in execution lead to erratic schedules that increase costs. Most importantly, this unpredictability makes talent management difficult. Innovation comes from enabling and resourcing brilliant people and granting them the freedom to explore new ideas. Innovative development takes time. Scientific breakthroughs are not predictable. As such, overall system maturation should be given the best chance to succeed through a steady research program that retains talented individuals over time.

Several theaters that present A2/AD challenges due to their integrated air defenses are also vast geographic regions with limited opportunities for US forward basing. As a result, long-range platforms are vitally important to future power projection. For example, B-21s must be purchased in significant quantity to support operational flexibility. The range limits of tactical fighters must be addressed and careful thought put into the logistical tail. Often, future battle scenarios are conceived with dozens of fifth-generation fighters and strike aircraft magically ready to penetrate the densest part of the A2/AD environment. Weapon detection and engagement zones are significantly wider for large aircraft, often denying the ability to have tanker support close enough for tactical fighters or traditional UAVs to be relevant. Future research should explore increasing tanker survivability to allow them to approach the forward edge of the battle. Nontraditional UAVs such as Gremlins launched by traditional long-range mobility platforms provide another viable option. Even if efforts are able to secure some forward basing options, priority must be given to platforms with range and penetration ability. Scenarios with quantities of tactical range fighters or traditional UAVs must be met with skepticism. It is time to ask the hard questions of how they get there. If the answer is air refueling and 20-hour duty days for the pilots in tactical, single-seat cockpits, that inflicts a serious human toll on performance and regeneration time. Air dominance in contested environments will require long-range manned platform hosts teaming with attritable tactical UAV partners that are not subject to fatigue. Even the term "fighter" may be antiquated, conjuring thoughts of small, highly maneuverable dogfighters. In the future battlespace, envisioning these platforms as manned nodes or sensor/shooters may be more informative.[9] Focused research should continue to develop long-range, manned control platforms.

The Strategic Technology Office at DARPA has committed itself to a system-of-systems approach out of necessity, but this also allows the agency to seize inherent opportunities. Fielding a force capable of defeating future adversaries at a price the American public can afford is a driving factor. This approach uses architectures networking unmanned, lower-cost, lower-capability platforms with optionally manned, higher-cost, higher-capability platforms. The lower-cost platforms are able to enhance the military effectiveness and survivability of higher-cost platforms while protecting the human in the force. Different types of platforms limit systemwide vulnerabilities. The lower-cost platforms can be bought in enough quantity that they can saturate defenses: Quantity becomes a quality of its own. This seizes initiative by imposing complexity and cost on the adversary. Open architecture and less investment risk enable quick innovation and development of the lower-cost platforms. New vehicles, sensors, and systems that are peripheral to the command-and-control core could be adapted quickly with little risk to the overall system.

The future A2/AD battlespace is layered and complex. Current platform-based strategies likely cannot achieve air dominance in this environment and are financially unsustainable. A radical shift to network-based system-of-systems approach can overcome these challenges. DARPA's investment in Gremlins, ALIAS, and CODE is paving the path toward a possible future. As a research organization, DARPA can only take this vision so far. For it to become a reality, the services must take up the torch and develop programs of record that support these efforts. Air Force senior leaders have repeatedly stated their commitment to this vision. However, overcoming years of inertia at lower levels will require sustained pressure.

Hypersonic Strike Weapons

A second way of dealing with an A2/AD environment is to use long-range standoff weapons that allow platforms to strike within the protected space without actually penetrating it themselves. Hypersonic flight is a vitally important and inevitable revolution in aerospace power based on a suite of technologies currently in development in the United States and abroad. Though routine manned hypersonic air vehicles are likely still several decades away, hypersonic strike weapons will be operational much sooner. Hypersonic flight generally refers to vehicles travelling in excess of Mach 5, roughly 3,600 miles per hour or one mile per second. While vehicles in this class face significant technical challenges due to extreme temperatures and thermal loadings and complex aerodynamic effects, they also potentially enjoy significant tactical advantages. By carefully considering the benefits and challenges of hypersonic vehicles and looking at current developmental projects, one can chart the proper course toward realization of hypersonic strike vehicles that will fundamentally alter the technical means of power projection.

Advances in infrared search and track and full-spectrum radar effectively deny penetration into certain regions for most platforms. Hypersonic standoff strike seeks to return the advantage to the attacker by holding targets at risk without endangering the launch platform. In addition, speeds in excess of one mile per second could enable unprecedented rapid response and flexibility. A single platform launching a volley of hypersonic strike weapons could simultaneously strike targets a thousand miles apart in less than 10 minutes from launch. This would allow commanders to penetrate an adversary's decision cycle, striking before they are able to orient and act. Rapid action is particularly critical when dealing with mobile targets or when leveraging surprise. Countering the tyranny of geography that vast regions present, hypersonic weapons shrink the flight time to targets, granting tactical agility. Rapid strike is a key component of Air Force doctrine, and hypersonic strike significantly extends the reach and lethality available to commanders.

A B-52 loaded with dozens of hypersonic strike weapons could effectively contribute in even the most defended environments by launching standoff weapons outside of the enemy's engagement zones. By enabling legacy platforms to participate in this "high-end" fight, the commander would gain significant flexibility. Developing weapons sized for launch from tactical platforms would further expand options available to commanders. True radar penetrators like the B-2 are extremely limited in quantity, which limits flexibility to respond in multiple regions. Furthermore, it is more cost-effective to invest in expendable weapons in quantities that achieve power-projection goals rather than purchasing large numbers of expensive platforms. This is not to say that these expensive platforms in some number are not necessary. However, leveraging significant standoff-strike capabilities reduces the number of penetrating platforms needed, a reality in a time of limited budgets. Finally, even the best low-observable technology is only as good as the next defensive advancement. Already, full-spectrum search and track limits the utility of our stealth platforms. As the never-ending, cat-and-mouse game between attackers and air defenses continues, having a potent standoff capability could provide an important insurance measure.

The hypersonic environment is epically hostile, resulting in significant technical challenges. At these speeds, gas molecules begin to disassociate, producing an ionized plasma around the vehicle. Sonic shock waves fold close to the body of the vehicle with strong entropy gradients creating flows that disturb the boundary layer. While understanding the physics of this is not essential to this discussion, it is important to note that many of the aerodynamic and thermodynamic models that have been developed over years of flying supersonic vehicles no longer apply in the hypersonic realm. Furthermore, kinematic heating is extreme, and slight miscalculations quickly lead to destructive melting and structural burn through. In the case of scramjet vehicles, fuel must be mixed and ignited with a supersonic flow of air in milliseconds. The analogy of lighting and sustaining a candle in a tornado is apt. At this point, many of these fundamental issues have been overcome by previous development programs expanding the knowledge base of hypersonic flight controls and thermodynamics. The next step for hypersonic strike weapons is building a reliable platform at a tactically relevant, affordable, expendable weapons price point. Further consideration for weaponizing a hypersonic vehicle will need to focus on communication, targeting sensors, affordable high-temperature materials, manufacturing methods, and operational concepts.

Other nations are pursuing hypersonic technologies also. For example, India is close to fielding the BrahMos-II, a hypersonic cruise missile (figure 3). Soon, hypersonic strike weapons will be a reality in the battlespace, and many of those weapons will be in the hands of potential adversaries. This underscores the importance of continued US development and highlights a corollary imperative: For many of the reasons already discussed, hypersonic weapons can be very difficult to defend against. Efforts must be made to understand adversary systems and develop effective defense strategies to mitigate potential threats. Simply winning the race to field the first hypersonic strike weapon does not address this future vulnerability.

Figure 3. India's BrahMos II hypersonic cruise missile. ("Model missiles BrahMos-II exhibition DefExpo-2014," *Defense and Aerospace News* [India], 5 February 2014.)

The Mitchell Institute for Aerospace Studies lays out key steps for the path forward in hypersonics based on a consistent and disciplined technology path.[10] The history of hypersonics is littered with exciting projects that overreached and failed, often spectacularly. Recent efforts such as the X-51A Waverider (figure 4) have been successful by setting more moderate, achievable goals and consistently advancing the state of the art. Continued work at DARPA and the Air Force Research Laboratory (AFRL) builds on that success and paves the way toward realizable fielded systems. To reach this goal, consistent research must continue in these programs—including developing adequate test and research facilities.

Hypersonic technology development requires wind tunnels and ranges that do not currently exist. Furthermore, continued technology maturation is needed for thermal management, materials and structures, and hypersonic flight controls and propulsion. Hypersonic weapons are no longer the stuff of science fiction. They will be here sooner than most people realize. These weapons offer a significant asymmetric advantage and must be considered in any future strategy. Ensuring the United States seizes this advantage requires awareness of the potential, a future operational vision, and consistent rigorous research.

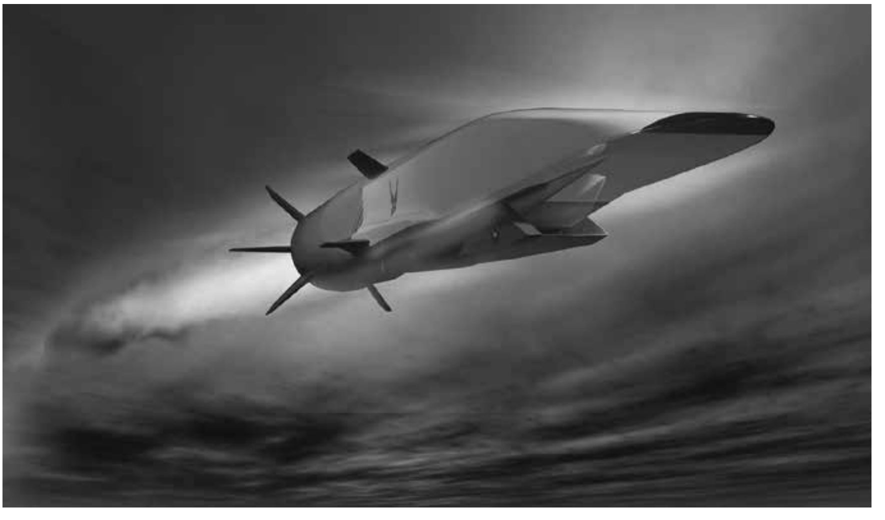

Figure 4. X-51A WaveRider. (United States Air Force, "X-51A WaveRider," http://www.af.mil/shared/media/photodb/photos/100520-F-9999B-111.jpg, accessed 20 May 2010.)

Directed Energy

One of the most disruptive trends of the last half century has been the steady rise of ubiquitous microelectronics. In the military realm this presents a significant challenge and an opportunity. Proliferation of emerging seeker technology threatens current aircraft defenses while corresponding advances in laser technology promise to deliver reliable high-energy lasers. This provides revolutionary new military capabilities countering next-generation sensors and creating offensive laser weapons. High-energy airborne lasers are a logical next step in aircraft defense and an important future offensive strike capability.

In the past, chemical lasers were the only laser option with enough power density to deliver a militarily significant beam in a size- and weight-limited environment. However, significant progress has been made over the past decade using fiber lasers. These solid-state lasers are more robust, more compact, and more suitable for a military environment than their chemical predecessors. A single fiber laser starts with electrical energy that is converted to high-power, high-beam-quality laser energy. Because the created beam is then contained in a fiber-optic cable, it can be transmitted flexibly and combined to create a beam of military significance.[11] Progress in fiber laser arrays, beam combination, and adaptive optics promises a future in high-energy lasers that is indeed very bright, with laser power perhaps on the order of hundreds of kilowatts.

Advanced imaging circuits, particularly focal-plane array sensors, present a significant threat to airborne platforms.[12] These advanced seeker heads are an immediate threat to air vehicles that high-energy lasers can address, and the threat demands a new paradigm in aircraft defense. Due to size, weight, and power considerations, large aircraft using next-generation high-power fiber lasers for defense are prime candidates for early adoption. Replacing current infrared countermeasures systems with a high-energy laser that destroys—rather than only jamming—incoming missiles would dramatically increase survivability in semipermissive environments. Continual advances in infrared counter countermeasures (IRCCM) make current-day missiles increasingly jam resistant. The proliferation of next-generation imaging seekers further complicates this problem. Moving from a concept of infrared jamming to physical destruction of the missile, future aircraft will be able to break the cycle of incremental improvements. Destroying a small antiaircraft missile that is close to the laser-bearing aircraft takes much less laser power than an offensive system striking targets of military interest at range. For this reason, defensive systems are a good first step in building operational high-energy laser systems. Using beam-combining methods, fiber-laser assemblies are imminently scalable; their output power is limited primarily by power and cooling available on the carrier platform. With continued research funding, current limitations facing offensive laser systems will be overcome in the next decade.

Offensive laser-strike capabilities introduce a host of significant potential tactical advantages. First, fiber-laser weapons using aircraft-generated electricity have a magazine size and duty cycle limited only by onboard power-generation capability. Second, despite what Hollywood may have depicted, lasers in clear air are invisible and silent. Third, laser weapons can be incredibly precise with real-time feedback continuously optimizing the strike location. Finally, with lasers propagating at the speed of light, strike time is nearly instantaneous. Though there are yet major technical challenges to overcome, these advantages warrant continued interest. The day is not far off where an AC-130 will silently disable an adversary's vehicle before a special operations raid. Silent, surgical, and persistent, laser strike provides significant options to military planners.

Another important technological advancement for airborne lasers is adaptive optics. This technology adjusts the output beam to compensate for atmospheric distortion, so after the beam propagates through the air it strikes a target with maximum focus. Traditionally, this has been done with a deformable mirror in the optical path. A wave-front sensor observes the propagated beam and uses feedback algorithms to deform the mirror until maximum intensity on target is achieved. The limiting factor in applying this technology is often the rate at which the mirror can be deformed. Even though the mirror may be able to deform many thousands of times per second, turbulent, chaotic phenomena can happen at even faster rates. Ongoing work will better characterize these flows to anticipate future conditions and feed forward corrections to the control system before they actually happen. Another method of performing adaptive optics is with phased arrays using separately controllable laser elements, as was demonstrated by the DARPA Excalibur program.

The DARPA Excalibur program significantly advanced the state of the art in high-energy lasers in several of these areas. In 2012 this program developed coherent optically phased arrays to enable scalable laser weapons. Using low-power, electrically driven, fiber-laser arrays, high beam quality was achieved through atmospheric turbulence. This was done in a form factor that was 10 times lighter and more compact than existing chemical-laser systems. Excalibur paved the way for ongoing research. Also, a systems-integration approach is being used to determine actual duty cycles, power draw, and cooling cycles for current systems.

Airborne lasers have in the past been the recipients of significant investment with little payoff.[13] Understandably, some senior leaders are skeptical that the technology is mature enough or that this time will be different. Fiber lasers with beam-combining and adaptive optics address many of the past concerns that sidelined previous work. The primary hurdle in realizing fielded systems at this point is a lack of vision. Building on recent successes, this is a medium-risk investment with a potentially high pay off as DARPA and AFRL continue to develop directed energy technologies. Building awareness in the operational community is critical to technology transition and adoption and operational concept development. Lasers present a novel weapons class. Work must be done to understand limitations and potential. The technology is now advanced enough that it is hard to imagine a future battlespace where lasers will not play a critical role. With this in mind, tactics, doctrine, and public policy should be developed now to pave the way for this inevitable future. Critical work being accomplished now at DARPA and AFRL must continue while tactical communities work through the operational ramifications of adding these new capabilities. Directed energy will be a major component of the future battlespace. That future must be considered in terms of operational employment, strategic policy, and international law. The means to that end are well on the way to being crafted today in labs across the nation.

Conclusion

The march of technology and world events present US armed forces with a myriad of significant challenges—and parallel opportunities. Each generation of military evolution has greatly increased lethality and survivability of individual weapons platforms but has also had a corresponding rise in unit cost. To address geographic flexibility and to provide capability to overwhelm layered defenses, large numbers of low-cost platforms provide a compelling alternative. Global economic trends and domestic pressures that constrain resources allocated to military spending lead to a unique moment where change is a strong imperative. By seizing this imperative, a radically different force structure could emerge that is more effective, less expensive, and carries less risk. Current work at forward-looking institutions such as DARPA presents one vision of a future battlespace architecture that shows potential to realize that goal.

In general, the vector inspired by current DARPA programs shows great promise to seize the technological advantage and spur a tighter innovation cycle to address volatile threats. This vision will not happen on its own. Departing from longstanding unsustainable acquisition trends, research in disaggregated capabilities, hypersonic strike weapons, and directed energy provides an alternate route. Today we must set out on the path to this new force structure to build a force that is viable in 2030. SSQ

Notes

1. Notably outside the scope of this paper—but absolutely critical to this future vision—are space-, cyber-, and sea-based power projection; full spectrum low observability; precision navigation and timing (PNT); quantum communications and computing; integrated circuit advancements; biological enhancement; maritime technologies; manufacturing and material sciences; and others.

2. Unless otherwise cited, information presented in this article is based on the author's personal experience working on these programs within DARPA and discussions with actual DARPA program managers.

3. Norman R. Augustine, *Augustine's Laws.* (Reston, VA: American Institute of Aeronautics and Astronautics Inc., 1997), 107.

4. Aaron Mehta, "Work Outlines Key Steps in Third Offset Tech Development," *Defense-News*, 14 December 2015, http://www.defensenews.com/story/defense/innovation/2015/12/14/work-third-offset-tech-development-pentagon-russia/77283732/.

5. For more information on the Gremlins program, see Daniel Pratt, "Gremlins" DARPA web site, n.d., http://www.darpa.mil/program/gremlins.

6. There is lack of consensus on what the terms *expendable*, *attritable*, and *recoverable* mean in this context. To be clear, *expendable* means a single-use munition or vehicle that is completely lost after one engagement—for example, traditional cruise missiles or a Super Coyote UAV. *Attritable* means that loss of individual members of the pack is acceptable in prosecuting a mission, and *recoverable* means that after the mission is accomplished any remaining vehicles return and are available for future missions.

7. For more information on the ALIAS program, see Daniel Pratt, "Aircrews Labor In-Cockpit Automation System (ALIAS)," DARPA web site, n.d., http://www.darpa.mil/program/aircrew-labor-in-cockpit-automation-system.

8. For more information on the CODE program, see Jean-Charles Ledé, "Collaborative Operations in Denied Environment (CODE)," DARPA web site, n.d., http://www.darpa.mil/program/collaborative-operations-in-denied-environment.

9. Lara Seligman, "Beyond the Fighter Jet: The Air Force of 2030," *Defense News*, 18 April 2016, http://www.defensenews.com/story/defense/air-space/2016/04/08/beyond-fighter-jet-air-force-2030/82767356/.

10. Richard P. Hallion, Curtis M. Bedke, and Marc V. Schanz, *Hypersonic Weapons and US National Security: A 21st Century Breakthrough* (Arlington, VA: Air Force Association, 2016), http://media.wix.com/ugd/a2dd91_b7016a5428ff42c8a21898ab9d0ec349.pdf

11. Tso Yee Fan, "Laser Beam Combining for High-Power High-Radiance Sources," *IEEE Journal of Selected Topics in Quantum Electronics* 11 no. 3 (May 2005: 567–77, doi: 10.1109/JSTQE.2005.850241.

12. Focal-plane array sensors that operate in the infrared spectrum were once the domain of relatively few specialized military labs. The arrays that could be manufactured had large pixels yielding poor resolution. They were produced in small batches and were prohibitively expensive. Due to advancements in integrated chip technology, it seems likely that many of these challenges will be overcome in the next decade, leading to widespread proliferation of high-resolution, inexpensive focal-plane array infrared sensors.

13. Jason D. Ellis, *Directed-Energy Weapons: Promise and Prospects* (Washington, DC: Center for a New American Security, April 2015), https://www.cnas.org/sites/default/files/publications-pdf/CNAS_Directed_Energy_Weapons_April-2015.pdf.

Book Essay

The Future of Artificial Intelligence

Allison Berke

Abstract

The first questions facing the development of artificial intelligence (AI), addressed by all three authors, are how likely it is that humanity will develop an artificial human-level intelligence at all, and when that might happen, with the implication that a human-level intelligence capable of utilizing abundantly available computational resources will quickly bootstrap itself into superintelligence. We need not imagine a doomsday scenario involving destructive, superintelligent AI to understand the difficulty of building safety and security into our digital tools.

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How to Create a Mind: The Secret of Human Thought Revealed by Ray Kurzweil. Penguin Books, 2012, 282 pp., $17.00.

Our Final Invention: Artificial Intelligence and the End of the Human Era by James Barrat. St. Martin's Griffin Press, 2013, 267 pp., $16.99.

Superintelligence: Paths, Dangers, Strategies by Nick Bostrom. Oxford University Press, 2014, 260 pp., $29.95.

Three recent popular science works explore the future of AI—examining its feasibility, its potential dangers, and its ethical and philosophical implications. Ray Kurzweil, an inventor, technologist, futurist, and AI pioneer—known for popularizing the concept of the *singularity* (a point at which technological progress in machine intelligence approaches runaway growth)—has in recent years devoted his efforts to machine learning and speech processing. Kurzweil's research, including that of companies he has founded, is centered on enabling computers to recognize speech and text, building individual capabilities necessary for general AI. In *How to Create a Mind*, Kurzweil summarizes recent advancements in neuroscience and software development to put forth an argument that the areas of the brain that produce a uniquely human intelligence—primarily the neocortex—are composed of a network of similar, hierarchically organized units responsible for executing nested pattern recognition algorithms. These algorithms can be translated into software via hierarchical hidden Markov models, and Kurzweil demonstrates that these models can be used to perform speech recognition and query analysis.[1] This approach to AI recognizes that rather than simulating an entire brain at the level of individual neurons, simulating its processes and results is computationally more efficient. The combined effect of Kurzweil's optimism and credentials gives the impression that AI is an attainable goal that technologists and inventors are inexorably approaching, a conclusion that may have spurred James Barrat, a documentary filmmaker with a focus on ancient history and inventions, to pen the case against AI in *Our Final Invention*. Barrat's interest in AI began when he interviewed Kurzweil in 2000, but his investigations into AI led to a more cautionary perspective, warning that superintelligent AI will be difficult or impossible to control, may be developed or motivated by the goals of our adversaries, and will likely resist or outmaneuver our efforts to design in controls and safety measures. Barrat points to many of the same technologies as Kurzweil—Siri, Apple's digital assistant; and Watson, IBM's *Jeopardy!*-winning, question-answering system factor prominently—but he anticipates a future in which Watson's descendants, tasked with improving human lives, ignore or misinterpret these instructions in favor of building more and better copies of themselves. This could lead, Barrat argues, to a depletion of the Earth's resources and the enslavement or eradication of humanity, as the self-improving AI departs for other planets in its quest to acquire more raw materials.

To this debate arrives Nick Bostrom, professor of philosophy at Oxford University and the founding director of Oxford's Future of Humanity Institute. Befitting his academic perspective, in *Superintelligence* Bostrom takes a broader view of AI development and outlines a framework for assessing the possibilities at each stage: how AI may be developed, how its intelligence can be measured, what problems AI will be used to address, where it may diverge from our intentions or abilities to control it, and what the implications of unleashing a superintelligent machine upon our society could be. Bostrom's book provides necessary context and vocabulary, allowing both sides of the debate to address the same questions.

The first questions facing the development of AI, addressed by all three authors, are how likely it is that humanity will develop an artificial human-level intelligence at all, and when that might happen, with the implication that a human-level intelligence capable of utilizing abundantly available computational resources will quickly bootstrap itself into superintelligence. Bostrom defers to the results of a survey of professionals, who place the development of human-level AI at 20 to 30 years in the future, a commonly postulated horizon that continually recedes as the technology in question fails to materialize. Researchers in the 1970s, after some of the first advances in machine learning and language processes, also predicted that human-level AI would be developed in 20 years. Kurzweil, befitting his position as a futurist, is invested in the fruition of this technology and cites his research on the exponential increases in related capabilities such as the number of transistors per chip, the number of operations per second performed by supercomputers, the cost of performing these calculations and of storing their output in digital memory, and the decreasing cost of transistors. His Law of Accelerating Returns proposes that the exponential growth we have observed thus far in the capacity and performance of computation technologies will impel a solution to the problem of digitally replicating human intelligence. Barrat's response to this prediction is to note that as long as we assign a nonzero probability to the development of AI, we must address its risks with the appropriate seriousness; a risk that threatens the existence of humanity, even at a low probability, is of greater urgency than a relatively certain but low- to moderate-level risk, such as the risk of a self-driving car injuring a pedestrian.

Having established AI as a problem worthy of discussion, the authors diverge in accordance with their interests. Kurzweil's assumption is that the reader will want to know how AI will be developed, with proofs of principle for the computational underpinnings of its methods. *How to Create a Mind* takes the reader on a tour of neocortical analysis, brain scanning, evolutionary algorithms, and programs like Siri and Watson that provide sophisticated solutions to carefully delineated problems of language analysis. Kurzweil touches briefly on the question of whether a human-level AI would be considered conscious; his conclusion is that, so long as the AI's responses are sufficiently convincing, we should not care, as qualia-like color perception and emotional experience are already subjective and internal. He hardly addresses whether the AI we build might destroy us. While acknowledging that nation-states have competitive incentives to build AI, to Kurzweil, AI will only be used to help humanity—as a symbiotic tool that will enhance our analytical and decision-making capabilities.

In contrast, Barrat sees the negative consequences of AI as intrinsic to its development, and he focuses instead on who will be motivated to construct an AI, what their motivations reveal about the goals they will program into their systems, and, therefore, how best to prepare for—or attempt to mitigate—the harms these systems will visit upon the world. Barrat draws sinister conclusions from the secrecy of large companies like Google, the funding aims of organizations like the Defense Advanced Research Projects Agency (DARPA), and the types of problems motivating defense contractors and foreign governments. While Kurzweil's AI will be a helpful savant—a child of Siri and Watson that aims to provide us with information while understanding our puns, accents, and wordplay—Barrat's AI is a killing machine, bent on global domination or unwittingly destroying the planet's resources to provide itself with more energy and silicon.

Which, then, is more likely? An AI that assists humanity and provides us with answers to problems we thought hopelessly intractable or an AI that remorselessly crushes us to better execute its code? The difficulty of answering this question stems from the fact that, as Bostrom outlines, both scenarios require us to evaluate concepts, like "superhuman intelligence," that exceed the scope of our experience. To define how we will recognize intelligence that is exponentially superior to ours, or the types of values and moral judgments with which we could imbue this intelligence to prevent it from harming us, we have to define concepts that have long stymied philosophers; presumably, if we all agreed completely on what outcomes are good for humanity, we would not need AI to tell us how to achieve them. The possibility of engineering initial conditions into our AI seedlings that will spur their development along moral and beneficial paths neglects the reality that we attempt to do this routinely, such as when we code software we assume is secure or even through the process of raising children—and are just as routinely surprised by unintended results. More prosaic goals, such as constructing an AI that can be kept isolated from other networks or an AI that does not seek to destroy other AIs are still subject to modes of failure that Bostrom characterizes as stemming from the available options for the motivations and capabilities that can be programmed into our AI.

Technologists may find such a philosophical conclusion unfulfilling, just as historians may find a preoccupation with the how, rather than the why, of AI development to be insufficiently imaginative. Kurzweil's and Barrat's works serve as complementary correctives, the former providing a solid base for understanding how we are approaching the development of AI and the latter a discussion of the hazards accompanying that approach. Bostrom's analysis requires more thought from the reader but provides a strong framework with which to organize that thought, stepping through the potential alternatives at each stage of AI development and deployment. Where all three volumes understandably fall short is in analogies to other technological developments—and attendant fears—that historically went unrealized. Technology skeptics occasioned an "AI winter" once, and those interested in the recent resurgence of funding and interest in AI are unwilling to dismiss it yet again as a goal too grandiose for debate. Yet there may be instructive parallels in the development of nuclear weapons or space travel; both were accompanied by grand and existentially threatening predictions that were averted by deliberate and strategic cooperation as well as by technological limitations and safeguards. Similarly, though Bostrom and Barrat describe AI component technologies, such as digital assistants or machine-learning algorithms that design circuits and identify faces, only to bolster the case that the development of full AI is fast approaching, the ethical problems involved in the control of AI are seen in microcosm in the question of what should happen when a self-driving car cannot avoid a crash or how Siri should respond to a suicidal user. We need not imagine a doomsday scenario involving destructive, superintelligent AI to understand the difficulty of building safety and security into our digital tools. SSQ

Notes

1. A Markov process is usually characterized as *memorylessness*: the probability distribution of the next state depends only on the current state and not on the sequence of events that preceded it. In a hidden Markov process, the current state is not visible, but the output is visible. See the *Wikipedia* entry at https://en.wikipedia.org/wiki/Hidden_Markov_model, accessed 14 July 2016.

Book Review

Mind Wars: Brain Science and the Military in the 21st Century by Jonathan D. Moreno. Bellevue Literary Press, 2012, 205 pp., $5.00.

Mind Wars is a fascinating book that sparks thought and debate concerning questions that should and must be asked as the future of warfare becomes present conflict. Jonathan Moreno is on the short list of individuals most qualified to provide the necessary expertise to cover this topic. Moreno has been a senior staff member for three presidential advisory commissions and has served on a number of Pentagon advisory committees. He is also an ethics professor at the University of Pennsylvania and the editor-in-chief at the Center for American Progress's online magazine *Science Progress*. Moreno begins the book by describing his childhood, which began a lifelong fascination in discovering the unknowns of brain science and later in life the mission of ensuring the ethics of future discoveries remains intact. *Mind Wars* spans the adventures of an entire career on the forefront of neuroscience debates concerning past, current, and future technological capabilities that enhance the world we live in and how we live in it.

Moreno does an excellent job of highlighting the necessity of answering ethical questions of enhancing technological capabilities that affect how war is waged and how life is lived by those affected. Throughout the book, Moreno raises questions through multiple examples of past experiments and new capabilities of advancing neuroscience capabilities that can truly impact every aspect of our lives. By raising questions of new, specific scientific theories and experiments, the answer becomes clear: steps must be taken prior to any advances in neuroscience capability to ensure proper precautions.

For example, one might think life-changing advances of prosthetic technology that help service members who have lost limbs only provide a positive option to a negative product of war. The ability to allow someone the capability to use a body part that was previously unusable is assuredly a great and joyous advance in technology. However, what happens if our prosthetic technology becomes more capable than the human body? There have already been reports of soldiers with bodily injuries—such as muscular disabilities—that prevent the soldier from serving in a mission-ready status but still maintain partial use of the limb who request to have it amputated and replaced with a prosthesis to return to a full mission-ready status. Another example is focused on internal capabilities. Work has long been under way to allow individuals a greater level of focus and attention to learn a topic more quickly. Many individuals also take medications to stay up longer or simply not feel so drowsy. These are just a few examples of a myriad of technological advances that allow the human body to be altered to perform at the desired level. At face value, most of the advances are simply enhancing human ability to perform. In the future, what happens if governments begin forcing soldiers to comply with certain enhancements so they are more capable than the enemy to ensure mission success? Moreno discusses the fact that soldiers specifically, more so than voluntary participants, could theoretically be forced to receive these enhancements in a future conflict. If these enhancements are made, should they be removed after military service is complete? These questions do not even begin to investigate the psychological effects of these bodily changes. The ripple effects of these advances from prosthetic technologies to enhanced thinking and learning capabilities extend much further than we even have the capability to predict, which is why these debates and discussions must occur now and not once these future capabilities become more common.

Moreno offers broad solutions to solve some of these issues but leaves much of the answering of these difficult questions to the reader. Ask nearly any expert concerned with military warfare in the twenty-first century, including Moreno, and one would learn that warfare is only becoming more complicated as science and technology continue to shape the way war is waged. These questions must be answered by those policy makers with the power to make change. Although slow and lengthier in parts than necessary, *Mind Wars* will assist the reader in uncovering possible risks of implementing future scientific advancements. At the very least, this book allows the reader the opportunity to reassess one's critical thinking capabilities of examining possible outcomes of future actions. Almost any individual involved with the future of warfare could benefit from Moreno's thoughtful and thorough examination of brain science affecting the military in the twenty-first century.

1st Lt William Morgan, USAF

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