

FORECASTING CHANGE IN MILITARY TECHNOLOGY, 2020-2040

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EXECUTIVE SUMMARY¹

What changes are likely in military technology over the next 20 years? This question is fascinating on its own terms. More importantly, answering it is crucial for making appropriate changes in U.S. and allied weaponry, military operations, wartime preparations, and defense budget priorities. To be sure, technology is advancing fast in many realms. But it is not enough to wave one's arms exuberantly about futuristic military possibilities. The stakes are too high. Defense resource decisions need to be based on concrete analysis that breaks down the categories of major military technological invention and innovation one by one and examines each. Presumably, those areas where things are changing fastest may warrant the most investment, as well as the most creative thinking about how to modify tactics and operational plans to exploit new opportunities (and mitigate new vulnerabilities that adversaries may develop as a result of these same likely advances). Building on the methodology employed in my earlier 2000 book, *Technological Change and the Future of Warfare*, and refined further in my recent paper, "A Retrospective on the So-Called Revolution in Military Affairs, 2000-2020," this paper attempts to look two decades into the future to aid in this important task for American defense planners.

My working hypothesis is that 20 years is long enough to represent a true extrapolation into the future. Yet it is also short enough that existing trends in laboratory research can help us understand the future without indulging in rampant speculation. Since many defense systems take a couple of decades to develop, it should not be an overly daunting task to gauge how the world might look, in terms of deployable military technology, 20 years from now. This approach is not foolproof, as discussed in my forthcoming book, but if undertaken with the proper degree of acknowledged uncertainty, can still be quite useful.

This paper's category-by-category examination of military technology employs the same basic framework that I developed in my book published in 2000, *Technological Change and the Future of Warfare*. The core of that book was an analysis of ongoing and likely future developments in 29 different types of military-related technologies. My goal was

1. This paper draws from Michael E. O'Hanlon, *The Senkaku Paradox: Risking Great Power War Over Small Stakes* (Washington, DC: Brookings Institution Press, forthcoming 2019).

to attempt to determine in which areas the pace of change was likely to be revolutionary over the following 20 years, versus high or moderate. Revolutionary change is defined, notionally, as a type and pace of progress that renders obsolete old weapons, tactics, and operational approaches while making new ones possible. My methodology began with a focus on the foundational concepts of physics, to understand the limits of the possible. I also examined the scientific, engineering, and defense literature on various types of technological research, to understand what was likely to be developed over the 2000-2020 time period. Finally, armed with my own initial estimates of key trends in those 29 areas, I then consulted with experts, including at several of the nation's major weapons laboratories, for their feedback and advice. With this research complete, I then argued in the book that in fact only two of the 29 categories of technology were likely to experience truly revolutionary change—and thus to create the potential for military revolution when combined with other kinds of available technologies as well as new operational and strategic concepts. Those two areas of predicted revolutionary advance were computer hardware and computer software.

As discussed further in my concurrent paper “A Retrospective on the So-Called Revolution in Military Affairs, 2000-2020,”² I have subsequently concluded that I was right about computers but should have added robotics to the list of technologies likely to experience radical change (my earlier estimate, in 2000, forecast a “high” pace of change for robotics such as unmanned aerial vehicles, rather than radical or revolutionary progress). Notably, there are now some 20,000 unmanned vehicles of various types in the Department of Defense's (DoD) inventory, and the various new uses to which they have been put during this century, from Iraq and Afghanistan to the broader Middle East and beyond, are remarkable. Enemy forces are increasingly using robotics, too.³

I should have also underscored the degree to which progress in computers could create vulnerabilities, as nations increasingly utilized computer systems and software that created potentially gaping weaknesses in their military capabilities. This point proved important enough that in retrospect I should have given it special and separate emphasis. Thus, in my earlier taxonomy, I had one important area of technology where I underestimated the potential for revolutionary advancement, and another where I should have underscored additional dimensions of likely change.

In the earlier book, I also predicted that another seven categories of technology would likely witness high change—chemical sensors, biological sensors, radio communications, laser communications, radio-frequency weapons, nonlethal weapons, and biological weapons. The remaining 19 categories of key military technologies, many of them sensor technologies or major components of weapons platforms like ground combat vehicles, aircraft, ships, and rockets, seemed likely to advance at only modest or moderate rates.⁴ In my concurrent paper, I revisit these prognostications one by one. In general, the thrust of my estimates seems to have been mostly correct, though with a number of specific imperfections in which progress that I had forecast to be high or rapid proved to be only moderate, or vice versa. Crucially, however, putting aside robotics, I do not believe that any of the remaining 26 areas of technology did in fact undergo revolutionary change.

2 Michael E. O'Hanlon, “A Retrospective on the So-Called Revolution in Military Affairs, 2000-2020,” (Washington, DC: Brookings Institution, 2018), <https://www.brookings.edu/research/a-retrospective-on-the-so-called-revolution-in-military-affairs-2000-2020>.

3 Brian K. Hall, “Autonomous Weapons Systems Safety,” *Joint Forces Quarterly* 86, (3rd quarter, 2017): 88.

4 Michael E. O'Hanlon, *Technological Change and the Future of Warfare* (Washington, DC: Brookings Institution Press, 2000), 65.

Two lessons emerge from this previous analysis. One, the approach I developed in the 2000 book appears useful. Assessing future trends in military technology by examining a number of fairly broad, yet also fairly specific and discrete areas of defense-related technology, and then integrating these individual findings into a broader framework for predicting future war, is valuable. This methodology discourages hyperbole based on cherry-picking areas of technology that may be most (or least) promising.⁵ It also helps to identify those specific technological enablers that are most likely to cause any radical change in broader military capabilities—to figure out what might drive a revolution in military affairs, should there be such a thing anytime soon.

Second, to the extent that there were flaws in my approach and my analysis, it is important to understand their origins, and attempt to take remedial action in any future prognostication. Most importantly, it was difficult to predict how military organizations would avail themselves of new technological opportunities—or, alternatively, to allow themselves to remain or become vulnerable in the face of new capabilities possessed by possible adversaries. In other words, the challenge was largely in predicting how entrepreneurial military organizations might, or might not, respond to transformational opportunities for better or worse.

In terms of robotics, U.S. military organizations responded with innovative and entrepreneurial acumen, creating new tactical methods to handle the challenges of complex counterinsurgency and counterterrorism operations. Other military organizations around the world have also made significant progress in this arena.

In regard to computers, however, modern militaries generally have not succeeded. Indeed, they carelessly allowed themselves to build Achilles' heels into their own systems, as well as their supporting national civilian infrastructure that is often essential to the operations of modern military forces. Thus, they have potentially made the performance of future weapons less dependable than past ones had been. In other words, they may even have set themselves back, though it is impossible to know for sure at this point, since we have not seen the kind of interstate warfare among near-peer competitors that would probably be needed to assess the hypothesis accurately.

Those operating in the classified world may have a greater sense than I of the vulnerabilities and opportunities that the United States now faces due to cyber technology. But even they cannot be sure because cyber vulnerabilities are not static. They are always evolving in a game of measures and countermeasures, even faster than in other areas of military operations characterized by these kinds of dynamics, such as electronic warfare. In addition, the ripple effects of any cyberattack often cannot be easily foreseen even when specific vulnerabilities are understood. There may also be important path dependencies about how different types of failures might collectively affect a larger system. It is difficult to evaluate these possibilities by examining individual vulnerabilities alone.

It is not surprising that forecasting the future would be hardest when complex concepts are involved and when large military organizations are the key actors. Scientists can invent new capabilities in ways that are often partially projectable and foreseeable over a 20-year time horizon based on what is known about their present research activities as well as opportunities opened up by the state of modern science and engineering. However, when it comes to combining technologies into systems and operational concepts that can

5 For a good, if controversial, recent warning about the perils of too much technophilia, see Martin Wolf, "Same As It Ever Was," *Foreign Affairs* 94, no. 4 (July/August 2015): 15-22.

be instrumental in fighting wars, the human dimension of organizational performance, influenced by the external combat environment as well as domestic and bureaucratic politics, introduces new variables into the mix, as the writings of Stephen Rosen, Thomas Ehrhard, Barry Posen, Stephen Biddle, and others attest. The Revolution in Military Affairs (RMA) debate of the 1990s underscored the reality that, while technology can provide the raw materials for military revolutions, those revolutions must ultimately be sparked by entrepreneurship and organizational adaptation. This was true historically, as with the inventions or transformations of the blitzkrieg, integrated air defense, aircraft carrier operations, amphibious assault, anti-submarine warfare systems, and the atomic bomb in the 1930s and 1940s. It remains true today.⁶

To preview the results of this paper, my overall assessment is that technological change of relevance to military innovation may be faster and more consequential in the next 20 years than it has proven to be over the last 20. Notably, it is entirely possible that the ongoing, rapid pace of computer innovation may make the next two decades more revolutionary than the last two. The dynamics in robotics and in cybersecurity discussed here may only intensify. They may be more fully exploited by modern military organizations. They will likely extend in important ways into the artificial intelligence (AI) realm as well. At least, an examination of the last 20 years would seem to suggest the potential for such an acceleration. That is particularly true in light of the fact that multiple countries (most notably China, but also Russia) now have the resources to compete with Western nations in military innovation. Some other areas of technology, perhaps most notably directed energy systems, hypersonic missiles, and certain types of advanced materials, could play important supplemental roles in making the next two decades a true period of military revolution, or at least of very fast and ongoing rapid transformation.

My assessment of trends in key areas of military-relevant technology is organized into four categories. The first is sensors, of many different types, which gather data of relevance to military operations. The second comprises the computer and communications systems that process and distribute that data. Third are major weapons platforms and key enabling technologies for those platforms. Fourth are other types of weapons systems and other technologies, many relatively new. Within these four general areas, all of the 29 sub-categories of technology that I employed in the 2000 book are retained here, in addition to 10 new sub-categories. Four of the 10 are within the computers and communications category: offensive cyber capabilities, systemic or “internet of things” networking, quantum computing, and artificial intelligence and big data. Two are within the projectiles, propulsion, and platforms category—battery-powered engines and satellites. Four more are within the final, miscellaneous category: chemical weapons, nanomaterials, 3D printing, and human enhancement devices as well as substances. I now proceed with this discussion, organized with the four major categories mentioned above.

6 See for example, H. A. Feiveson, *Scientists Against Time: The Role of Scientists in World War II* (Bloomington, IN: Archway Publishing, 2018); Thomas P. Ehrhard, “Air Force UAVs: The Secret History,” (Arlington, VA: Mitchell Institute, 2010), http://notreally.info/transport/drones/aars/pdf/MS_UAV_0710.pdf; Montgomery C. Meigs, *Slide Rules and Submarines: American Scientists and Subsurface Warfare in World War II* (Honolulu, HI: University Press of the Pacific, 2002); Barry R. Posen, *The Sources of Military Doctrine: France, Britain, and Germany Between the World Wars* (Ithaca, NY: Cornell University Press, 1984); Andrew F. Krepinevich, “From Cavalry to Computer: The Pattern of Military Revolutions,” *The National Interest*, September 1, 1994, <http://nationalinterest.org/article/cavalry-to-computer-the-pattern-of-military-revolutions-848>; Williamson Murray, “Thinking about Revolutions in Military Affairs,” *Joint Forces Quarterly*, (Summer 1997), <http://www.dtic.mil/dtic/tr/fulltext/u2/a354177.pdf>; and Stephen Peter Rosen, *Winning the Next War: Innovation and the Modern Military* (Ithaca, NY: Cornell University Press, 1991).

FIGURE 1: PROJECTED ADVANCES IN KEY DEPLOYABLE TECHNOLOGIES, 2020-2040

	Moderate	High	Revolutionary
<i>Sensors</i>			
Chemical sensors		X	
Biological sensors		X	
Optical, infrared, and UV sensors	X		
Radar and radio sensors	X		
Sound, sonar, and motion sensors	X		
Magnetic detection	X		
Particle beams (as sensors)	X		
<i>Computers and communications</i>			
Computer hardware			X
Computer software			X
Offensive cyber operations			X
System of systems/Internet of things			X
Radio communications	X		
Laser communications		X	
Artificial intelligence/Big data			X
Quantum computing		X	
<i>Projectiles, propulsion, and platforms</i>			
Robotics and autonomous systems			X
Missiles	X		
Explosives		X	
Fuels	X		
Jet engines	X		
Internal-combustion engines	X		
Battery-powered engines		X	
Rockets		X	
Ships	X		
Armor		X	
Stealth		X	
Satellites		X	
<i>Other weapons and key technologies</i>			
Radio-frequency weapons	X		
Nonlethal weapons		X	
Biological weapons		X	
Chemical weapons		X	
Other weapons of mass destruction	X		
Particle beams (as weapons)	X		
Electric guns, rail guns		X	
Lasers		X	

	Moderate	High	Revolutionary
<i>Other weapons and key technologies (cont.)</i>			
Nanomaterials		X	
3D printing/Additive manufacturing		X	
Human enhancement devices and substances		X	

Note: 1) The terms moderate, high and revolutionary are subjective and somewhat imprecise. In general terms, technologies showing moderate advances might improve their performance by a few percent or at most a couple of tens of percent—in terms of speed, range, lethality, or other defining characteristics—between 2020 and 2040. Those experiencing high advances will be able to accomplish tasks on the battlefield far better than before—perhaps by 50 to 100 percent, to the extent improved performance can be so quantified. Finally, technology areas in which revolutionary advances occur will be able to accomplish important battlefield tasks that they cannot now even attempt.

SENSORS

In warfare, targets obviously need to be found and tracked in order to be attacked and destroyed. Other battlefield information is crucial too, such as that concerning terrain and weather, as well as the locations of civilian populations, key infrastructure, and friendly forces.

Sensors are the military technologies that provide information about all the above. I briefly examine eight general types here. Three categories—radar and radio, optical/infrared/ultraviolet (UV) sensors, and magnetic detectors—make use of one type or another of electromagnetic radiation. Another type, sonar, involves sound in water. Particle beams are a fifth category. Biological sensors, chemical sensors, and nuclear materials detectors round out the list.

Begin with this last group of sensors, those for detecting weapons of mass destruction. Just as in the past two decades, progress over the next two seems likely to be gradual.

Current research on chemical weapons detection focuses on finding more trace amounts in a given fixed site, and on making detectors more portable and affordable, rather than on developing fundamentally different methods of detecting chemicals from a distance.⁷ Sandia Lab's pulsed-discharge ionization detector (PDID) is an example of such a technology. The chief dilemma in finding chemical weapons, related to the challenge for locating biological materials, is that to identify a chemical compound, one generally needs direct access to it, to employ a method of identification such as gas chromatography. Laser spectroscopy from a distance or other such methods of remote interrogation are not particularly promising for most battlefield applications; such means could generally only work if a chemical were released into the atmosphere.⁸

Biological weapons detectors are improving. To date, they have not only needed direct access to any pathogens to identify them, but enough time to watch the pathogens grow

7 See for example, Arnie Heller, "Responding to a Terrorist Attack," (Livermore, CA: Lawrence Livermore National Laboratory, March 2010), <https://str.llnl.gov/Mar10/pdfs/3.10.1.pdf>; Anne M. Stark, "Livermore Researchers Develop Battery-Less Chemical Detector," *Lawrence Livermore National Laboratory*, April 6, 2011, <https://www.llnl.gov/news/livermore-researchers-develop-battery-less-chemical-detector>; "Researching New Detectors for Chemical, Biological Threats," *Sandia National Laboratories*, September 5, 2013, https://share-ng.sandia.gov/news/resources/news_releases/threat_detectors/#.WiBKufnyupo; and Cory Nealon, "New Sensing Tech Could Help Detect Diseases, Fraudulent Art, Chemical Weapons," *PhysOrg*, June 1, 2015, <https://phys.org/news/2015-06-tech-diseases-fraudulent-art-chemical.html>.

8 Joey Cheng, "Small, Deep-UV Lasers Could Detect Biological and Chemical Agents on the Battlefield," *Defense Systems*, March 24, 2014, <https://defensesystems.com/articles/2014/03/24/darpa-luster-chem-bio-detection.aspx>.

or otherwise reveal their identity through natural biological functions. Given advances in microbiology and genetics, it seems likely that much faster methods will be developed in the next two decades. By “seeing” a pathogen’s DNA more quickly, methods of identification can be reduced in part to more digital and computational realms where computers can bring their enormous powers to bear and dramatically accelerate the identification process.

Still, progress seems likely to be moderate or moderately fast, rather than revolutionary—at least in terms of its battlefield implications. In the short term, the Department of Homeland Security (DHS) is prototyping a two-tier biological detection sensor system but it will still take up to 15 minutes to detect and identify a relatively narrow range of potential pathogens at close-in range. That is not dramatically different from where technologies stood two decades ago, even if there has been considerable effort in making systems somewhat more deployable and user-friendly.⁹ For example, the basic BioWatch technology, on which current systems are based, largely reflects modifications to technology and concepts first deployed in 2003, shortly after the anthrax attacks that followed 9/11.¹⁰

Some new ideas are being pursued. For example, the Lawrence Livermore National Laboratory has created the Lawrence Livermore Microbial Detection Array that examines DNA directly (without requiring cultures) and searches for literally thousands of bacteria, viruses, and fungi. To date, however, it has been used for very specialized applications and is not at the basis of current DHS or DoD deployable systems; it also requires 24 hours to detect a pathogen.¹¹ Identifying organisms is inherently a complex business.¹² As a recent review article put it, “For further progress in the biosensors field we need revolutionary ideas in the development of novel target recognition strategies. ... We also need new paradigms for the identification and detection of existing or emerging pathogenic microorganisms, unknown toxins and viral threat agents.” Since even future biological pathogen detectors will require direct physical access to agents, their strategic role for intelligence or targeting from long ranges will remain limited, even if their tactical usefulness improves.¹³

Detection of nuclear materials remains difficult given the basic physics of the signature. Key nuclear materials in a weapon do not give off large amounts of radiation, and they can be shielded by materials like lead so that whatever they do emit is prevented from escaping to the general environment.

Nuclear forensics are improving through a number of sophisticated chemical and computational methods that can make it easier to determine where a given fissile material or waste product may have originated, through improvements in the materials used in sensors such as stilbene crystals.¹⁴ But the processes still require being

9 “Detect to Protect Bio-Aerosol Detection Systems,” (Washington, DC): Department of Homeland Security Science and Technology Directorate, April 2016), https://www.dhs.gov/sites/default/files/publications/Detect%20to%20Protect%20Bio-Aerosol%20Detection%20Systems_0.pdf.

10 Reginald Brothers and Kathryn H. Brinsfield, “Joint Testimony,” (testimony, U.S. House of Homeland Security Subcommittee on Emergency Preparedness, Response, and Communications, Washington, DC, February 11, 2016), <http://docs.house.gov/meetings/HM/HM12/20160211/104326/HMTG-114-HM12-Wstate-BrinsfieldK-20160211.pdf>.

11 Stephen Wampler, “LLNL Biodetection System Bound for Space,” *Lawrence Livermore National Laboratory*, April 28, 2016, <https://www.llnl.gov/news/llnl-biodetection-system-bound-space>.

12 Kim E. Sapsford et al., “Sensors for detecting biological agents,” *Materials Today* 11, no. 3 (March 2008): 38-49, <http://www.sciencedirect.com/science/article/pii/S136970210870018X>.

13 Jeffrey Kirsch et al., “Biosensor Technology: Recent Advances in Threat Agent Detection and Medicine,” *Chem Soc Rev* 42, no. 22 (2013): 8733-8768, <https://pubs.rsc.org/en/content/articlelanding/2013/cs/c3cs60141b/unauth#divAbstract>.

14 Allan Chen, “Revealing the Presence of Hidden Nuclear Materials,” *Lawrence Livermore National Laboratory*,

close enough to the materials that their relatively feeble radioactive signatures can be detected and distinguished from normal background radiation.¹⁵ Thus, it is not surprising that the 2018 Nuclear Posture Review would aspire to “sustain and build upon” the 57,000 radiation detectors operating at U.S. ports, border crossings, and key interior sites, rather than to propose pursuit of any breakthrough technology. There is no alternative, and there almost surely will be no alternative, to proximate monitoring and interrogation.¹⁶

Next, consider sonar—an acronym taken from the phrase “sound navigation and ranging”—that is, the process of using underwater pressure or sound waves to detect objects beneath the surface of a given body of water. Sonar is a mature technology, with the basic concept and technologies involved being similar today to what they have been for decades.

Still, sonar is improving gradually, largely through better signals processing capabilities and through expanded use of robotics to proliferate sensors. These trends could accelerate in the coming years.¹⁷ One telling indicator of the expected progress in sonar is that, after decades when one might have already thought the method to be obsolete, dolphins may finally soon earn their retirement from the mine-warfare enterprise. The Knifefish, an unmanned underwater vehicle using low-frequency synthetic-aperture sonar, may be among the pioneer vessels with this capability.¹⁸ Low-frequency sonar, with lengthy receiver arrays that are physically separate from the emitter, is also showing promise for long-range active detection. Aided by the sophisticated signals-processing capabilities of modern computing, it is showing the potential to increase detection ranges against certain types of objects in at least some circumstances by up to an order of magnitude or so. The unclassified literature on the subject describes its capabilities in regard to finding fish, not enemy submarines. But advocates envision finding targets of interest 100 kilometers away or further.¹⁹

Another concept being explored by the U.S. Naval Undersea Warfare Center in Newport, Rhode Island would focus on the physics of the water around mobile sonar sensors. The system uses a cavitator to change the flow of water near the sensors, reducing their exposure to noise and thus improving their sensitivity to an actual target signal.²⁰ Yet another sonar improvement being investigated would apply to shallow waters that are often noisy. By studying those waters at different times of year and understanding how sound ricochets through them, improvements can be made in how an actual signal of a specific vessel might be better separated from the noise.²¹

January/February 2017, <https://str.llnl.gov/january-2017/zaitseva>.

15 Michael Levi, *On Nuclear Terrorism* (Cambridge, MA: Harvard University Press, 2007); and Elizabeth Keegan et al., “Nuclear Forensics: Scientific Analysis Supporting Law Enforcement and Nuclear Security Investigations,” *Analytical Chemistry* 88, no. 3 (2016): 1496-1505, <http://pubs.acs.org/doi/abs/10.1021/acs.analchem.5b02915>.

16 Jim Mattis, “Nuclear Posture Review 2018” (Washington, DC: Department of Defense, February 2018), 67, <https://www.defense.gov/News/SpecialReports/2018NuclearPostureReview.aspx>.

17 John Keller, “New Era Dawns in ASW as Manned and Unmanned Submarines Team for Bistatic Sonar,” *Military and Aerospace Electronics*, October 24, 2017, <http://www.militaryaerospace.com/articles/print/volume-28/issue-10/news/news/new-era-dawns-in-asw-as-manned-and-unmanned-submarines-team-for-bistatic-sonar.html>.

18 “Retirement in Sight for Mine-Hunting Dolphins,” *Aviation Week and Space Technology*, January 28, 2013, <http://aviationweek.com/awin/retirement-sight-mine-hunting-dolphins>.

19 Nicholas Makris, “New Sonar Technology Reveals City-Size Schools of Fish,” *IEEE Spectrum*, July 26, 2011, <https://spectrum.ieee.org/energy/environment/new-sonar-technology-reveals-citysize-schools-of-fish>.

20 Technology Partnership Office, “NUWC Division Newport Commercialization Opportunities,” (Newport, RI: Naval Undersea Warfare Center Division Newport, 2012), <http://www.navsea.navy.mil/Portals/103/Documents/NUWC-Newport/TechPartnering/CommercializationOpportunities2012.pdf>.

21 Daniel Perry, “Navy Researchers, Reservists Evaluate Novel Passive Sonar Surveillance Methods,” *U.S. Naval Research Laboratory*, February 20, 2013, <https://www.nrl.navy.mil/media/news-releases/2013/navy-researchers-reservists-evaluate-novel-passive-sonar-surveillance-methods>.

All that said, in regard to sonar's role in finding submarines, progress in making subs quieter has continued as well. A net assessment of sonar as a tool of anti-submarine warfare must therefore be less than bullish. It is for such reasons that the U.S. Navy flatly declares, in an official document on sonar, that in previous eras, passive sonar against noisy submarines could usually find them before they came within weapons-firing range of U.S. assets, whereas today, active sonar is needed to achieve the same early warning.²² It is hard to find Navy documents that suggest any radically different expectations about the future.

Consider the broad category of sensors employing the electromagnetic spectrum to collect information. This includes visible light sensors such as lasers as well as ultraviolet and infrared sensors in the near-visible part of the spectrum; radio and radar; and magnetic detection methods.

A broad observation that can be offered about such sensors is that they will run head-on into basic physics in the future just as they have in the past. Despite the extremely impressive existing technologies that exploit these various kinds of electromagnetic radiation, the simple fact is that they are rapidly attenuated or blocked by a number of prevalent materials on Earth. Water is perhaps the most significant. That means that most soil is also difficult to penetrate very far with any kind of sensor employing such radiation. Ultraviolet light, gamma rays, and x-rays fare even worse than visible light. Radar is also severely compromised by water, though extremely low frequency (ELF) waves are a partial exception and can penetrate nearly 10 times further than visible light.²³

All of these kinds of radiation require a direct line of sight to any target. Radar curves modestly in the atmosphere, but it is the chief exception to this broad generalization, and only a partial one. One consequence of this fact is that such sensors are also blocked by the Earth and limited by its curvature for many purposes. A radar on land, or on an airplane, or in a low-altitude Earth orbit, can only see so far when searching for an object on or near the Earth's surface. The math is simple, and comes straight from the Pythagorean Theorem, combined with the fact that the Earth's diameter is about 8,000 miles:

$$\text{Radar horizon} \sim (90)(\text{Square root of radar altitude})$$

This means that for a high-flying aircraft at 9 miles (about 48,000 feet) altitude, the radar horizon would be about 270 miles, meaning that, for example, a ship at that horizontal distance below the aircraft would be just barely perceptible, whereas a ship 300 miles away would be hidden from view by the curvature of the Earth. The radar horizon would be about 180 miles for a medium-altitude aircraft at 4 miles (about 21,000 feet) height, while it would be 1,800 miles for a low-Earth orbit satellite at 400 miles altitude. Because of the refraction, or bending, of radar in the Earth's atmosphere, as noted above, actual ranges might be slightly greater than the above—as much as 30 percent more, at some wavelengths. But then again, atmospheric attenuation could also shorten the range. On balance, the above formula is a good first approximation.²⁴

22 "Sound Navigation and Ranging (SONAR)," U.S. Navy, <http://www.public.navy.mil/usff/environmental/Pages/Sonar.aspx>.

23 J.D. Jackson, *Classical Electrodynamics*, second edition (New York: John Wiley and Sons, 1975), 290-292.

24 J.C. Toomay, *Radar Principles for the Non-Specialist*, second edition (Mendham, NJ: SciTech Publishing, 1998).

Metal is another fairly unyielding barrier to electromagnetic radiation. Leaves, thin wood, and other materials with some water content may allow a certain modest transmission but even here, there is no getting around the fact that any water content will rapidly attenuate radiation.²⁵

Of course, there is impressive ongoing progress, though it needs to be viewed against these basic physical constraints on the plausible performance of future sensors. Laser sensor technology will continue to become smaller, cheaper, and thus more readily usable in multiple tactical systems on the battlefield.²⁶ For example, lasers are not only in use now in artillery like the Copperhead, but also in mortar systems, too.²⁷ Laser radar, or lidar, will also find new applications, such as helping robots and other unmanned systems “see.”²⁸ It may become more commonly used in relatively shallow-water anti-submarine warfare, too.²⁹

Similar progress is being observed with infrared technologies, which are becoming, and will continue to become, cheaper and more widely available as well.³⁰ Then there are various specific new applications. For example, optical sensors may soon be deployed within bullets to allow them to steer toward targets they have previously locked onto, using small fins. They can do so even when wind or other perturbations affect flight trajectory.³¹

Magnetic detectors are improving, with a number of new applications useful as compasses or other types of functions in small devices. However, the ability to find militarily significant objects in radically new ways appears to be advancing gradually. As one review article put it, “The development of magnetic sensor technology has been slow and gradual.”³² That can be expected to continue.

25 Duncan Brown, “Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar,” (Laurel, MD: Johns Hopkins University Applied Physics Laboratory, July 2014), 15.

26 Mark Sullivan, “Apple Is Working Hard on An iPhone Rear-Facing 3D Laser for AR and Autofocus: Source,” *Fast Company*, July 12, 2017, <https://www.fastcompany.com/40440342/apple-is-working-hard-on-an-iphone-8-rear-facing-3d-laser-for-ar-and-autofocus-source>.

27 Christopher F. Foss, “Smart ammo: precision-guided munitions for field,” *Jane’s Defence Weekly*, 2015, http://www.janes360.com/images/assets/423/54423/precision-guided_munitions_for_field_artillery.pdf; Audra Calloway, “Army Developing Laser-Guided, Precision Mortar,” *U.S. Army*, March 3, 2017, www.army.mil/article/183491/army_developing_laser_guided_precision_mortar; and Robert Sherman, “M712 Copperhead,” *Federation of American Scientists*, <https://fas.org/man/dod-101/sys/land/m712.htm>.

28 Christopher V. Poulton and Michael R. Watts, “MIT and DARPA Pack Lidar Sensor Onto Single Chip,” *IEEE Spectrum*, August 4, 2016, <https://spectrum.ieee.org/tech-talk/semiconductors/optoelectronics/mit-lidar-on-a-chip>.

29 Graham Templeton, “A Deeper Look into Lasers, Particle Beams, and the Future of War,” *Extreme Tech*, April 25, 2013, <https://www.extremetech.com/extreme/153585-a-deeper-look-into-lasers-particle-beams-and-the-future-of-war>; Weilin Hou, “Blue-Green Laser Communications Critical Technologies for Anti-Submarine Warfare and Network Centric Operations,” *International Defence, Security, and Technology*, September 8, 2017, <http://idstch.com/home5/international-defence-security-and-technology/technology/photonics/blue-green-laser-communications-and-lidar-critical-technologies-for-anti-submarine-warfare-and-network-centric-operations>; and Peter Coates, “LIDAR: An Anti-Submarine Warfare Sensor,” *Submarine Matters*, January 16, 2014, <http://gentleseas.blogspot.com/2014/01/lidar-anti-submarine-warfare-sensor.html>.

30 Dexter Johnson, “Infrared Technology on the Cheap with Nanostructured Gratings,” *IEEE Spectrum*, May 26, 2016, <https://spectrum.ieee.org/nanoclast/semiconductors/optoelectronics/infrared-technology-on-the-cheap-with-nanostructured-gratings>.

31 Annabs Sanchez, “Watch DARPA’s New Self-Guided Bullets Turn in Mid-Flight, Following Their Target,” *Futurism*, March 17, 2016, <https://futurism.com/wanted-curved-bullet-now-a-reality/>; and Benjamin Sutherland, “Military Technology: Wizardry and Asymmetry,” in *Megatech: Technology in 2050*, ed. Daniel Franklin (London: Profile Books, 2017), 132.

32 Pavel Ripka and Michal Janosek, “Advances in Magnetic Field Sensors,” *IEEE Sensors Journal* 10, no. 6 (June 2010): 1108-1116, <http://ieeexplore.ieee.org/document/5443656/?reload=true>.

Magnetic detectors, as well as new uses of microwave devices and lasers, are also potentially useful in new concepts of anti-submarine warfare. Bioluminescence and wake-detection methodologies have also been investigated and some may remain of interest, including to Russia.³³ However, these methods seem unlikely to work at long range against deeply submerged submarines; their benefits are more likely to be tactical and local. One possible exception to this sweeping statement is wake-detection sensor systems, given the more inherently long-range phenomenology inherent in the basic concept of how the sensor operates. But by changing direction frequently, operating at greater depth at times, and otherwise avoiding straight-line steady movement under calm surface conditions, submarines may be able to take effective countermeasures.³⁴

Radar is still making forward strides. For example, synthetic-aperture radar (by which the movement of a radar creates the effect of a much larger aperture system, once signals are integrated over a substantial distance) can now be used to detect moving objects. This development represents in effect a more clever exploitation of data that was already available before, rather than a breakthrough in basic physics or engineering. Similarly, smaller radars can now be netted together to create the equivalent capability to that previously provided only by a larger system. That might, for example, allow a family of unmanned “Reapers” with Ground Moving Target Indicator capability to replace today’s Joint Surveillance and Target Attack Radar System, among other such applications.³⁵

In another recent application that continues to be refined (and to proliferate), radar altimeters can increasingly be used to optimize the detonation point of warheads to maximize their odds of destroying a given target—compensating for the computed inaccuracy of a given flight trajectory by last-minute adjustments to the height of the burst of the ordnance. This technology is applicable, for example, to re-entry vehicles carrying nuclear warheads.³⁶ Yet another new application of radar with implications that are still being developed is the use of small radar systems mounted on armored vehicles to detect and coordinate defenses against incoming threats. The Israeli Trophy system is an early example of this approach.³⁷

Multi-spectral radar is also being more widely developed and applied, motivated in part by the desire to find stealth aircraft by surveying a wider range of radar frequencies, improving the sensitivity of receivers, and looking toward aircraft from a variety of angles (some of which may present less stealthy perspectives of a given aircraft). That said, these improvements are most likely effective at shorter ranges. They do not eliminate the benefits of stealth altogether and will not do so. They certainly have not discouraged aircraft manufacturers from continuing to depend on stealth in cutting-edge systems despite its cost and complexity.³⁸ The improved radar systems are also likely to continue

33 Norman Polmar and Edward C. Whitman, “Russia Poses a Nonacoustic Threat to U.S. Subs,” *Proceedings* 143, no. 10 (October 2017): 26-30, <https://www.usni.org/magazines/proceedings/2017-10/russia-poses-nonacoustic-threat-us-subs>.

34 Technology Partnership Office, “NUWC Division Newport Commercialization Opportunities,” 10.

35 Lara Seligman, “U.S. Air Force’s Future Battlefield Edge Hinges on MQ-9 Reaper,” *Aviation Week and Space Technology*, March 12-25, 2018, 23-24.

36 Keir A. Lieber and Daryl G. Press, “The New Era of Counterforce: Technological Change and the Future of Nuclear Deterrence,” *International Security* 41, no. 4 (Spring 2017): 20-40.

37 Joseph Trevithick, “The U.S. Army Buys Israeli Trophy System so Its Tanks Can Blast Incoming Projectiles,” *The Drive*, September 29, 2017, <http://www.thedrive.com/the-war-zone/14748/us-army-buys-israeli-trophy-system-so-its-tanks-can-blast-incoming-projectiles>.

38 V.K. Saxena, “Stealth and Counter-Stealth: Some Emerging Thoughts and Continuing Debates,” *Journal of Defence Studies* 6, no. 3 (July 2012): 19-28, https://idsa.in/jds/6_3_2012_StealthandCounterstealthSomeEmergingThoughtsandContinuingDebates_VKSaxena; and Gabriel Dominguez, “China Develops Photonics-Based Radar,” *Jane’s Defence Weekly*, June 28, 2017, 16.

to be countered and challenged by computer-facilitated improvements in miniaturized decoys and jammers with increasingly autonomous capabilities, expendable and thus widely deployable given their small size.³⁹

Particle beams of various kinds as sensors are improving. For example, a pilot project at the Port of Boston uses a concept developed by two Massachusetts Institute of Technology (MIT) physicists involving nuclear resonance fluorescence, which employs a neutron beam to interrogate cargo. It is able to discern objects inside of closed containers much better than x-rays.

But the basic reality is that these active systems are inherently short-range in their phenomenology and their potential because they must generate a high-energy beam which tends to disperse or be absorbed by numerous materials at fairly short ranges.

Systems like the MIT/Port of Boston detector noted above still require proximate access to the objects being examined.⁴⁰

COMPUTERS, COMMUNICATIONS, AND ROBOTICS

Modern militaries, especially America's, have become extremely reliant on moving vast amounts of data around the battlefield as a normal part of operations. This has happened largely as the spread of computers, fiber optic cables, and other technologies has gone unopposed by the likes of al-Qaida and the Taliban—enemies that, whatever their strengths in other domains, are not able to compete on the high-technology battlefield with the United States, or disrupt its use of advanced data and communications systems.

These happy trends will not continue in any future warfare against more advanced militaries. To be sure, some new and exciting technologies may further aid tactical as well as theater-level and strategic communications. Laser communications systems, for example, could make an important difference, especially in space where clouds and other obstacles are not an impediment.⁴¹ Frequency-hopping radios with advanced computers coordinating the dance from one frequency to another are increasingly capable. Even if the radio technology per se is fairly mature, better computers allow levels of performance that were not previously possible. And innovations from the commercial world of mobile communications and their advanced networks that allow for “network-hopping” as well as other efficiencies will make the networks more robust and dependable against certain types of disruptions.⁴²

However, the disruptions themselves will become much more threatening. Jamming, possible attacks on fiber-optic undersea cables as well as satellites (discussed more

39 Angus Batey, “Miniature Electronics and Antennas Open the Door to New Set of Decoys,” *Aviation Week and Space Technology*, September 4-17, 2017, 40-43; Bryan Clark, Mark Gunzinger, and Jesse Sloman, “Winning in the Gray Zone: Using Electromagnetic Warfare to Regain Escalation Dominance,” (Washington, DC: Center for Strategic and Budgetary Assessments, 2017), 23-26, <http://csbaonline.org/research/publications/winning-in-the-gray-zone-using-electromagnetic-warfare-to-regain-escalation/publication>.

40 Robert Draper, “They Are Watching You—and Everything Else on the Planet,” *National Geographic*, February 2018, <https://www.nationalgeographic.com/magazine/2018/02/surveillance-watching-you>.

41 David W. Young et al., “Development and Demonstration of Laser Communications Systems,” *Johns Hopkins APL Technical Digest* 33, no. 2 (2015), www.jhuapl.techdigest; George Leopold, “Laser Comms from Space Gets Another Test,” *Defense Systems*, February 17, 2017, <https://defensesystems.com/articles/2017/02/17/spacelaser.aspx>; and Sydney J. Freedberg, Jr., “Say It With Lasers: \$45 Million DoD Prize for Optical Coms,” *Breaking Defense*, May 30, 2017, <https://breakingdefense.com/2017/05/say-it-with-lasers-45m-dod-prize-for-optical-coms>.

42 Seth Spoenlein, et al., “Path of Greatest Resilience,” *Army ALT Magazine*, February 2, 2018, <https://asc.army.mil/web/path-of-greatest-resilience/>.

below), and cyberattacks on the software of the radios and other systems used for communications are all serious worries, to say nothing of a high-altitude, nuclear-induced electromagnetic pulse.⁴³ Even when communications systems within a small unit survive enemy attack, or find themselves outside the targeted zone of intense jamming, communications with central authority may suffer. It is because of such concerns, for example, that the Army's Maneuver Warfare Center of Excellence at Fort Benning, Georgia is examining concepts of future operations in which a brigade might be cut off from divisional or corps headquarters for an extended period, and have to function entirely on its own during that time.⁴⁴

In regard to computers, rapid progress will likely continue. "Moore's Law," which states that the capacity and speed of computers will double every 18 to 24 months, may or may not hold quite as it has for several decades, but rapid progress seems likely to continue. Around 1970, several thousand transistors could be built onto a given chip; by 2000 the figure was roughly 10 million, and by 2015 or so it exceeded 1 billion.⁴⁵ Even if the pace of advance slows, it will not stop. And countless ways to take advantage of all this computing capacity that is already available will continue to be invented, with huge undeveloped potential in many areas.

For example, improved computing power can allow a multitude of satellites and other sensors to have their data synthesized automatically through various algorithms and artificial intelligence. This kind of effort may be further accelerated if the Department of Defense is successful in building up its relationships with Silicon Valley and other centers of computer excellence through innovations like the Defense Innovation Unit Experimental (DIUx).⁴⁶ These kinds of multi-platform networks can help mitigate the dangers associated with anti-satellite (ASAT) weapons attacking large, high-value military assets that previously had few if any backups.⁴⁷

Reflecting its awareness of what is becoming possible, the Department of Defense increased overall annual spending on artificial intelligence, big data, quantum computing, and related endeavors from \$5.6 billion to \$7.4 billion between 2012 and 2017. Former Deputy Secretary of Defense Robert Work has asserted that these areas of technological progress are at the heart of the so-called "third offset" that he and other recent Pentagon officials have championed.⁴⁸ Secretary of Defense Jim Mattis' 2018 National Defense Strategy evidences similar priorities. The odds in favor

43 U.S. Army, "Techniques for Tactical Radio Operations," (Washington, DC: Department of the Army, January 2016), http://www.apd.army.mil/epubs/DR_pubs/DR_a/pdf/ARN3871_ATP%206-02.53%20FINAL%20WEB.pdf; David Axe, "Failure to Communicate: Inside the Army's Doomed Quest for the 'Perfect' Radio," *Center for Public Integrity*, May 19, 2014, <https://www.publicintegrity.org/2012/01/10/7816/failure-communicate-inside-armys-doomed-quest-perfect-radio>; and James Hasik, "Avoiding Despair About Military Radio Communications Is the First Step Towards Robust Solutions," *Real Clear Defense*, July 24, 2017, https://www.realcleardefense.com/articles/2017/07/24/avoiding-despair-about-military-radio-communications-is-the-first-step-towards-robust-solutions_111884.html.

44 Briefing at the Army's Maneuver Warfare Center of Excellence, Fort Benning, GA, December 13, 2017.

45 M. Mitchell Waldrop, "The Chips are Down for Moore's Law," *Nature*, February 9, 2016, <http://www.nature.com/news/the-chips-are-down-for-moore-s-law-1.19338>; Rose Hansen, "A Center of Excellence Prepares for Sierra," *Science and Technology Review*, March 2017, 5-11.

46 Jacquelyn Schneider, "Swiping Left on Silicon Valley: New Commercial Analogies for Defense Innovation," *War on the Rocks*, May 16, 2017, <https://warontherocks.com/2017/05/swiping-left-on-silicon-valley-new-commercial-analogies-for-defense-innovation/>.

47 Duncan Brown, "Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar," 32-33.

48 Robert O. Work, "Artificial Intelligence, Big Data and Cloud Taxonomy," *Govini*, 2017, 1-9, www.govini.com/research-item/dod-artificial-intelligence-and-big-data-taxonomy; and Aaron Mehta, "Google's Schmidt: US Losing Edge in AI to China," *Defense News*, November 2, 2017, <https://www.c4isrnet.com/it-networks/2017/11/02/china-on-path-to-eclipse-us-with-ai-warns-google-head>.

of major breakthroughs are high for the next two decades.⁴⁹ AI systems are basically computers that can “learn” how to do things through a process of trial and error with some mechanism for telling them when they are right and when they are wrong—such as picking out missiles in photographs, or people in crowds, as with the Pentagon’s “Project Maven”—and then applying what they have learned to diagnose future data.⁵⁰

Largely as a result of the computer revolution, robotics will continue to improve dramatically.⁵¹ Already, of course, self-driving vehicles are possible. Soon, a number are likely to be built for specific military purposes like tactical resupply on the battlefield. The Army’s “Wingman” may be one example.⁵² Wingman is also being adapted to carry weapons at least for tests (albeit with real human soldiers in the decisionmaking loop).⁵³ And of course, it may not end there. The vice chairman of the Joint Chiefs of Staff, General Paul Selva, has recently argued that the United States could be about a decade away from having the capacity to build an autonomous robot that could decide when to shoot and whom to kill—though he also asserted that the United States had no plans actually to build such a creature.⁵⁴

Other robotics with more specific functions surely will be built. They will include advanced sensor systems, often acting as networks or “swarms.” In the air, they could also involve stealthier unmanned aerial vehicles (UAVs) with long range, usable as penetrating sensors, to give just one example.⁵⁵ On the sea, future robotics could include unmanned surface vessels for intelligence gathering, mine clearing, and possible local point defense against threats like fast-attack craft. Indeed, a RAND report in 2013 found there were already 63 unmanned surface vessels that had been developed and tested. Underwater robotic devices (unmanned underwater vehicles or UUVs), like the Defense Advanced Research Projects Agency’s (DARPA) “Sea Hunter,” could for example perform search functions associated with anti-submarine warfare and mine warfare.⁵⁶ It is already possible to talk somewhat precisely and realistically about how the U.S. Navy’s future fleet might include substantial numbers of unmanned surface and underwater vessels; a team of researchers including Bryan Clark and Bryan McGrath has recently

49 James Somers, “Is AI Riding a One-Trick Pony?” *MIT Technology Review*, September 29, 2017, www.technologyreview.com/s/608911/is-ai-riding-a-one-trick-pony.

50 Jack Shanahan, “Project Maven Brings AI to the Fight against ISIS,” *Bulletin of the Atomic Scientists*, December 21, 2017, <https://thebulletin.org/project-maven-brings-ai-fight-against-isis11374>; and Phil Stewart, “Deep in the Pentagon, a Secret AI Program to Find Hidden Nuclear Missiles,” *Reuters*, June 5, 2018, <https://www.reuters.com/article/us-usa-pentagon-missiles-ai-insight/deep-in-the-pentagon-a-secret-ai-program-to-find-hidden-nuclear-missiles-idUSKCN1J114J>.

51 For a good general overview of this subject and related matters that goes beyond the military sphere, see Darrell M. West, *The Future of Work: Robots, AI, and Automation* (Washington, DC: Brookings Institution Press, 2018).

52 Thomas B. Udvare, “Wingman is the First Step toward Weaponized Robotics,” *Army ALT Magazine*, January 16, 2018, <https://asc.army.mil/web/news-alt-jfm18-wingman-is-first-step-toward-weaponized-robotics/>; Hector Montes, et al., “Energy Efficiency Hexapod Walking Robot for Humanitarian Demining,” *Industrial Robot* 44, no. 4 (2016), www.emeraldinsight.com/doi/pdfplus/10.1108/IR-11-2016-0281; Robert Wall, “Armies Race to Deploy Drone, Self-Driving Tech on the Battlefield,” *The Wall Street Journal*, October 29, 2017, www.wsj.com/articles/armies-race-to-deploy-drone-self-driving-tech-on-the-battlefield-1509274803; and Scott Savitz, “Rethink Mine Countermeasures,” *Proceedings* 143, no. 7 (July 2017), www.usni.org/print/91134.

53 Thomas B. Udvare, “Wingman Is First Step toward Weaponized Robotics.”

54 Matthew Rosenberg and John Markoff, “The Pentagon’s ‘Terminator Conundrum’: Robots that Could Kill on Their Own,” *The New York Times*, October 25, 2016, <https://www.nytimes.com/2016/10/26/us/pentagon-artificial-intelligence-terminator.html>.

55 Austin Long and Brendan Rittenhouse Green, “Stalking the Secure Second Strike: Intelligence, Counterforce, and Nuclear Strategy,” *Journal of Strategic Studies* 38, nos. 1-2 (2015): 38-73.

56 Paul Scharre, *Army of None: Autonomous Weapons and the Future of War* (New York: W.W. Norton, 2018); Anika Torruella, “USN Seeks to Fill SSN Shortfalls with Unmanned Capabilities,” *Jane’s Defence Weekly*, July 5, 2017, 11; and Scott Savitz et al., “U.S. Navy Employment Options for Unmanned Surface Vehicles,” (Santa Monica, CA: RAND Corporation, 2013), xiv-xxv, https://www.rand.org/pubs/research_reports/RR384.html.

recommended a future fleet with 40 of each, for example.⁵⁷ The Navy is increasingly thinking of how to deploy its littoral combat ships with families of unmanned ships and other robotics.⁵⁸ Some UUVs could have long persistence and low signature even within close proximity of an enemy's shores.⁵⁹ A \$100,000 ocean glider recently crossed the Atlantic; promising concepts could cut that cost for UUVs by a factor of 10.⁶⁰

Even if General Selva's terminator is not built, robotics will in some cases likely be given the decisionmaking authority to decide when to use force. This highly fraught subject requires careful ethical and legal oversight, to be sure, and the associated risks are serious. Yet the speed at which military operations must occur will create incentives not to have a person in the decisionmaking loop in many cases.⁶¹ Whatever the United States may prefer, restrictions on automated uses of violent force would also appear relatively difficult to negotiate (even if desirable), given likely opposition from Russia and quite possibly other nations.⁶² Moreover, given progress in Russia and China, it is far from clear that the United States will be the lead innovator in artificial intelligence in the years ahead, with some warning that one or both of these countries may soon set the pace in AI—and thus also in warfighting robotics.⁶³

For example, small robots that can operate as swarms on land, in the air, or in the water may be given certain leeway to decide when to operate their lethal capabilities. By communicating with each other, and processing information about the enemy in real time, they could concentrate attacks where defenses are weakest, in a form of combat that John Allen and Amir Husain call "hyperwar" because of its speed and intensity.⁶⁴ Other types of swarms could attack parked aircraft; even small explosives, precisely detonated, could disable wings or engines or produce secondary and much larger explosions. Many countries will have the capacity to do such things in the coming 20 years.⁶⁵ Even if the United States tries to avoid using such swarms for lethal and offensive purposes, it may elect to employ them as defensive shields (say, against a North Korean artillery attack on Seoul) or as jamming aids to accompany penetrating aircraft. With UAVs that can fly 10 hours and 100 kilometers now costing only in the hundreds of thousands of dollars, and quadcopters with ranges of a kilometer more or less costing in the hundreds of dollars, the trend lines are clear—and the affordability

57 Bryan Clark and Bryan McGrath, "A Guide to the Fleet the United States Needs," *War on the Rocks*, February 9, 2017, <https://warontherocks.com/2017/02/a-guide-to-the-fleet-the-united-states-needs/>.

58 Kris Osborn, "Navy Littoral Combat Ship to Operate Swarms of Attack Drone Ships," *Warrior Maven*, March 28, 2018, <https://www.themaven.net/warriormaven/sea/navy-littoral-combat-ship-to-operate-swarms-of-attack-drone-ships-cSVfXZfBME2bm1dTX1tsw>.

59 Shawn Brimley, "Arresting the Erosion of America's Military Edge," (Washington, DC: Center for a New American Security, December 2015), 17, <https://s3.amazonaws.com/files.cnas.org/documents/While-We-Can-151207.pdf?mtime=20160906082559>.

60 T.X. Hammes, "The Future of Conflict," in *Charting a Course: Strategic Choices for a New Administration*, ed. R.D. Hooker, Jr. (Washington, DC: National Defense University Press, 2016), 25-27.

61 Matthew Rosenberg and John Markoff, "The Pentagon's 'Terminator Conundrum,'"

62 Patrick Tucker, "Russia to the United Nations: Don't Try to Stop Us from Building Killer Robots," *Defense One*, November 21, 2017, www.defenseone.com/technology/2017/11/russia-united-nations-dont-try-stop-us-buying-killer-robots/142734; and "Special Report: The Future of War," *The Economist*, January 27, 2018, 4.

63 Elsa B. Kania, "Battlefield Singularity: Artificial Intelligence, Military Revolution, and China's Future Military Power," (Washington, DC: Center for a New American Security, November 2017), <https://www.cnas.org/publications/reports/battlefield-singularity-artificial-intelligence-military-revolution-and-chinas-future-military-power>.

64 John Allen and Amir Husain, "On Hyperwar," *Proceedings* 143, no. 7 (July 2017), www.usni.org/print/91129; Jules Hurst, "Robotic Swarms in Offensive Maneuver," *Joint Forces Quarterly* 87, no. 4 (4th quarter, 2017): 105-111; Graham Warwick, "Powerful Pairing," *Aviation Week and Space Technology*, November 27-December 10, 2017, 35-36; and Graham Warwick, "Swarm Enabler," *Aviation Week and Space Technology*, April 3-16, 2017, 31-32.

65 T.X. Hammes, "The Future of Conflict."

of using many drones in an organized way is evident.⁶⁶ Although defenses against such robotics will surely be built, too, at present they are underdeveloped against possible small UAV swarms.⁶⁷ And unless area defense allows for a certain part of the sky, sea, or land effectively to be swept clear of any robotics within a certain zone, it seems statistically likely that some offensive UAVs will survive a defense's efforts to neutralize them—meaning that their capabilities to act as a swarm, even if perhaps a weakened one, will probably remain.

Robotics with artificial intelligence may also deploy on the battlefield in close partnership with real humans. These robotics could be paired one for one, or in larger numbers, under the control and for the purposes of a single soldier or unit.⁶⁸

As noted, with the progress in computers has come far greater cyber vulnerability. By effectively building Achilles' heels into everything they operate, modern militaries have created huge opportunities for their potential enemies. The fact that everyone is vulnerable, in some sense, is no guarantee of protection. Deterrence of some actions is not impossible in cyberspace, but it is surely difficult, and likely to fail in many important situations.⁶⁹ Vulnerabilities may vary across countries based on the different types of software employed in their military systems and different relative abilities of their respective offensive hacking units. Distressingly, the United States may be among the most vulnerable, given how much it has computerized in modern times, often somewhat carelessly it must be said, and often with software of questionable resilience.⁷⁰ A country figuring out how to integrate temporarily crippling cyberattack plans into an integrated operational concept may, even if still vulnerable to reprisal itself, be able to achieve dramatic success in the opening (and perhaps decisive) phases of a war. A military and a national infrastructure with key systems plugged into the internet, running on flawed software, and often employing a simple password system for user access rather than a two-factor authentication system is inherently vulnerable.⁷¹ This is precisely the situation the United States and most of its major allies face today. Faced with such a situation, in a future conflict, an enemy is likely to roll the dice and attempt large-scale cyberattacks—even if, in crossing such a threshold, it opens itself up to inevitable retaliation in kind.⁷²

Uncertainty abounds in the cyber domain. Software vulnerabilities that might exist at one time could be patched up subsequently, even as others emerge. Much of the information about these weaknesses is both highly technical and highly classified,

66 Ben Knight, "A Guide to Military Drones," *Deutsche Welle*, June 30, 2017, <http://www.dw.com/en/a-guide-to-military-drones/a-39441185>.

67 Kelsey Atherton, "As Counter-UAS Gains Ground, Swarm Threat Looms," *Aviation Week and Space Technology*, March 26-April 8, 2018, 36-37.

68 Alexander Kott, "The Artificial Becomes Real," *Army ALT Magazine*, January 18, 2018, 90-95.

69 Joseph S. Nye Jr., "Deterrence and Dissuasion in Cyberspace," *International Security* 41, no. 3 (Winter 2016/2017): 44-71.

70 Nigel Inkster, "Measuring Military Cyber Power," *Survival* 59, no. 4 (August-September 2017): 32; and Damien Dodge, "We Need Cyberspace Damage Control," *Proceedings* 143, no. 11 (November 2017): 61-65.

71 Tunku Varadarajan, "Report from the Cyberwar Front Lines," *The Wall Street Journal*, December 29, 2017, <https://www.wsj.com/articles/report-from-the-cyberwar-front-lines-1514586268>.

72 Erica D. Borghard and Shawn W. Lonergan, "The Logic of Coercion in Cyberspace," *Security Studies* 26, no. 3 (2017): 452-481; Travis Sharp, "Theorizing Cyber Coercion: The 2014 North Korean Operation Against Sony," *Journal of Strategic Studies* 40, (April 11, 2017): 898-926, <https://www.tandfonline.com/doi/full/10.1080/01402390.2017.1307741>; David D. Kirkpatrick, "British Cybersecurity Chief Warns of Russian Hacking," *The New York Times*, November 14, 2017, <https://www.nytimes.com/2017/11/14/world/europe/britain-russia-cybersecurity-hacking.html>; and Nicole Perlroth, "Hackers Are Targeting Nuclear Facilities, Homeland Security Department and FBI Say," *The New York Times*, July 6, 2017, <https://www.nytimes.com/2017/07/06/technology/nuclear-plant-hack-report.html>.

making it hard to assess a net vulnerability for the armed forces as a whole.⁷³ The overall situation today though is, on balance, very worrisome. A Defense Science Board study in early 2017 asserted that virtually no major U.S. weapons system had cyber systems that could be confidently vouched for.⁷⁴

A separate type of problem related to the same basic phenomenon of ongoing progress in computers and electronics is the vulnerability of domestic infrastructure and military weaponry to an electromagnetic pulse (EMP) from a high-altitude nuclear explosion. (U.S. systems could also be vulnerable to severe solar storms of a type that can typically occur once a century or so.) These vulnerabilities may be growing because smaller and smaller electronics are progressively more vulnerable to a given electric insult, and because as the Cold War recedes in time, the perceived likelihood of an EMP attack may decline. American strategists, military services, and weapons manufacturers may delude themselves into a false sense of perceived invulnerability, believing that an EMP attack would be seen as tantamount to a direct nuclear attack against populations and hence too risky. It is debatable whether all adversaries would in fact make such a calculation; as such, U.S. vulnerabilities in this area could easily grow further.⁷⁵

Communications systems are also highly vulnerable to jamming from sophisticated electronic warfare technologies. Digital electronics are amplifying and accelerating these challenges to the point where, in recent years, some Department of Defense research and development documents have prioritized electronic warfare as among the most rapidly changing and threatening of technological developments.⁷⁶

PROJECTILES, PROPULSION, AND PLATFORMS

Lumping together major vehicles, ships, aircraft, rockets, missiles, and the various engines and fuels that propel these large platforms, what can we usefully prognosticate about their likely progress over the next two decades?

Many of the new capabilities that will be in the field in 2040 are already foreseeable—and programmatically planned—even today. Thus, prognostication is not so hard in some ways, particularly for major weapons platforms of the type emphasized in this section.

Perhaps the long time required to design, test, build, and field major weapons platforms is in part a flaw of the U.S. weapons acquisition system. However, it is also not clear that platform technology is advancing so fast as to require a more supple and fast-moving process. As former Deputy Secretary of Defense William Lynn argued in a forum at Brookings in 2015, the Department of Defense may get a mediocre grade for “anything touched by Moore’s Law,” given that electronics and computers are advancing so fast, but it arguably does pretty well in regard to bending metal and building vehicles, ships,

73 Michael Frankel, James Scouras, and Antonio De Simone, “Assessing the Risk of Catastrophic Cyber Attack: Lessons from the Electromagnetic Pulse Commission,” (Laurel, MD: Johns Hopkins University Applied Physics Laboratory, 2015), <https://pdfs.semanticscholar.org/bda9/16313363cf775f9a06dd8d5195caf6a60c63.pdf>; and Robert McMillan, “Cyber Experts Identify Malware that Could Disrupt U.S. Power Grid,” *The Wall Street Journal*, June 12, 2017, <https://www.wsj.com/articles/cyber-experts-identify-malware-that-could-disrupt-u-s-power-grid-1497271444>.

74 Defense Science Board, “Task Force on Cyber Deterrence,” (Washington, DC: Department of Defense, February 2017), https://www.acq.osd.mil/dsb/reports/2010s/DSB-CyberDeterrenceReport_02-28-17_Final.pdf.

75 Duncan Brown, “Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar,” 17-24; and for a good overview, see Sukeyuki Ichimasa, “Threat of Cascading ‘Permanent Blackout’ Effects and High Altitude Electromagnetic Pulse (HEMP),” *NIDS Journal of Defense and Security*, no. 17 (December 2016): 3-20.

76 “DoD Research and Engineering Enterprise,” (Washington, DC: Department of Defense, May 2014), 3, [https://www.acq.osd.mil/chieftechologist/publications/docs/ASD\(R&E\)_Strategic_Guidance_May_2014.pdf](https://www.acq.osd.mil/chieftechologist/publications/docs/ASD(R&E)_Strategic_Guidance_May_2014.pdf).

and planes.⁷⁷ In any case, for many large platforms, even modest progress in the speed of acquisition would not change the fact that most systems that will be in service in the 2040s are already being researched today.

To begin this quick survey, consider first transport aircraft. They are likely to improve, but only modestly and gradually. Various possible innovations in areas such as structural materials for fuselages and wings, as well as engine technology, may improve performance—but typically by 10 to 25 percent, not 50 to 100 percent, in terms of various key metrics.⁷⁸

Progress in missiles is ongoing. Today's air-to-air missiles, for example, can now range 200 miles and reach speeds of Mach 6, in some cases.⁷⁹ The most interesting developments in the coming years are likely in the realm of hypersonic vehicles (those exceeding Mach 5) that may become capable of longer-range or even global strike operations over the time frame of interest in this paper. That could put any target on Earth within reach in less than an hour of decision and launch. They would likely employ scramjet and/or boost-glide technologies, which are expected to become substantially more affordable and capable. Scramjets use a rocket to attain high speeds, then an air-breathing engine to sustain the speed; boost-glide systems attain rapid speeds at high altitudes, then glide to target. While the United States will likely develop important new capabilities in this realm, so could China and Russia and perhaps other states. Indeed, as of early 2018, according to U.S. Under Secretary of Defense for Research and Engineering Michael Griffin, China has done 20 times as many hypersonic tests to date as the United States.⁸⁰ Weapons are now starting to be tested in the realm of Mach 8 to Mach 10 (6,000 or more miles per hour).⁸¹ Maneuverable and homing re-entry vehicles are already a reality on some types of ballistic missiles (for use, for example, against ships) and will likely continue to improve and gain greater usage, including by countries such as China.⁸²

Prototypes are also being developed for an aircraft with a combined conventional turbine engine with dual-mode ramjet/scramjet propulsion. The former would be used early in flight; the latter would kick in at higher speeds. Indeed, hypersonic aircraft reaching Mach 6 (in contrast to today's fighters in the Mach 2+ range) may become a possibility in the coming 20 years. In other words, they may become as fast as today's air-to-air missiles, especially if pilots can be left out of the cockpits and scramjet technology can be made affordable for them. Whether such systems truly wind up proving feasible, affordable, and effective in combat remains to be seen.⁸³

77 Proceedings of a panel discussion at Brookings, "Acquisition Reform: Increasing Competition, Cutting Costs, and Out-Innovating the Enemy," Brookings Institution, April 13, 2015, <https://www.brookings.edu/events/acquisition-reform-increasing-competition-cutting-costs-and-out-innovating-the-enemy>.

78 Thomas S. Grose, "Reshaping Flight for Fuel Efficiency: Five Technologies on the Runway," *National Geographic*, April 23, 2013, available at <https://news.nationalgeographic.com/news/energy/2013/04/130423-reshaping-flight-for-fuel-efficiency/>; and Lara Seligman, "Future Fighter," *Aviation Week and Space Technology*, September 4-17, 2017.

79 Jeffrey Lin and P.W. Singer, "China Is Testing a New Long-Range, Air-to-Air Missile that Could Thwart U.S. Plans for Air Warfare," *Popular Science*, November 22, 2016, <https://www.popsci.com/china-new-long-range-air-to-air-missile>.

80 Daniel Wasserbly, "Eyeing China, Hypersonic Technology is U.S. DoD's Top Development Priority," *Jane's Defence Weekly*, March 14, 2018, 4.

81 Robert Haffa and Anand Datla, "Hypersonic Weapons: Appraising the 'Third Offset,'" (Washington, DC: American Enterprise Institute, April 2017), <https://www.aei.org/publication/hypersonic-weapons-appraising-the-third-offset/>; Kyle Mizokami, "The U.S. and Australia Conducted a Secretive Hypersonic Missile Test," *Popular Mechanics*, July 18, 2017, www.popularmechanics.com/military/research/a27384/us-australia-hypersonic-missile-test; Guy Norris, "Boeing's Hyper Hope," *Aviation Week and Space Technology*, January 29-February 11, 2018, 20-21; and Guy Norris, "Prime Time: With Tripled High-Speed Research Budget, U.S. Air Force Spells Out Its Operational Hypersonic Needs," *Aviation Week and Space Technology*, August 14-September 3, 2017, 57-58.

82 Richard D. Fisher, Jr., "Chinese Resurgence: Beijing Returns to Larger Defense Budgets," *Aviation Week and Space Technology*, December 25, 2017-January 14, 2018, 56.

83 Guy Norris, "Hypersonic Skunk," *Aviation Week and Space Technology*, June 12-25, 2017, 26.

Consider ground vehicles, and several key trends in their underlying technologies. In engines for cars and light trucks, efficiency as measured in horsepower per volume of engine size has improved roughly a third this century so far, roughly the same pace per decade as in the latter quarter of the 20th century.⁸⁴ Tank engines have progressed at similar proportionate rates.⁸⁵ A 2014 paper by a well-known expert in the field projected progress of 2 to 5 percent in each of a dozen or so major elements of the functioning of an engine in the years ahead—hardly insignificant, especially if combined together, but not revolutionary in character either.⁸⁶

As for armor for heavy combat vehicles, most of the main innovations in widespread use today—depleted uranium armor, explosive-reactive armor, ceramic materials—were developed in the late 20th century. Today's newer concepts involve ideas such as laser defenses, perhaps more than armor itself. Progress will also occur by adopting recent innovations in armor more broadly and widely across key military vehicles.⁸⁷ This pace of innovation may however be roughly matched by progress in ordnance used to attack armor, including the greater introduction of nanomaterials into explosives as well as the expanded use of explosively-formed penetrators (which focus their power in a given direction for greater effect).

Next, consider large rockets. Any discussion here must begin with a sober realization that despite various predictions of revolutionary change in the 1990s and 2000s, change has been slow. Costs per pound of payload placed into orbit have remained similar to what they have been since the days of the Saturn rockets and Apollo program.⁸⁸ Many of the systems still in operation—Atlas, Delta IV, Athena, Minotaur, Pegasus, Taurus—were already in use in the 1990s; some even employ Minuteman or “Peacekeeper”/MX surplus missiles, often built in the 1970s and 1980s, as boosters.⁸⁹ To be sure, much greater progress could well loom, as reusable rockets show promise through the efforts of firms like SpaceX and Blue Sky. It is plausible that reusable rockets may ultimately cut costs by 50 percent or more (given the relative fraction of rocket cost attributable to the rocket body and main guidance systems, which are in principle reusable, versus the fuel and other specific preparations required anew for each launch, which are not). SpaceX claims that its huge Falcon Heavy rocket will cut costs by more than 75 percent

84 Gurpreet Singh, “Overview of the DOE Advanced Combustion Energy R&D Program,” (Washington, DC: Department of Energy, June 16, 2014), https://www.energy.gov/sites/prod/files/2014/09/f18/ace_rd_overview_2014_amr.pdf; Jerald A. Caton, “Maximum Efficiencies for Internal Combustion Engines: Thermodynamic Limitations,” *International Journal of Engine Research*, (October 2017), <http://journals.sagepub.com/doi/pdf/10.1177/1468087417737700>.

85 Alec Wahlman and Brian M. Drinkwine, “The M1 Abrams: Today and Tomorrow,” *Military Review* November-December 2014, http://www.armyupress.army.mil/Portals/7/military-review/Archives/English/MilitaryReview_20141231_art006.pdf.

86 John B. Heywood, “Improving Engine Efficiency and Fuels: An Overview,” (conference presentation, Baltimore, MD, February 2014), [https://crao.org/workshops/2014AFEE/Final%20Presentations/Day%201%20Intro%20Presentations/11-1%20Heywood,%20John%20-%20Presentation%20\[Compatibility%20Mode\].pdf](https://crao.org/workshops/2014AFEE/Final%20Presentations/Day%201%20Intro%20Presentations/11-1%20Heywood,%20John%20-%20Presentation%20[Compatibility%20Mode].pdf).

87 Chun Hong Kelvin Yap, “The Impact of Armor on the Design, Utilization and Survivability of Ground Vehicles: The History of Armor Development and Use,” (Monterey, CA: Naval Postgraduate School, 2012), <http://dtic.mil/dtic/tr/fulltext/u2/a567418.pdf>; and Sydney J. Freedberg, Jr., “Milley’s Future Tank: Railguns, Robotics, and Ultra-Light Armor,” *Breaking Defense*, July 27, 2017, <https://breakingdefense.com/2017/07/railguns-robotics-ultra-light-armor-general-milleys-future-tank>.

88 Paul B. Rehms, “Alternatives for Future U.S. Space-Launch Capabilities,” (Washington, DC: Congressional Budget Office, 2006), 11, 19, <https://www.cbo.gov/sites/default/files/109th-congress-2005-2006/reports/10-09-spacelaunch.pdf>; Peter B. de Selding, “SpaceX’s New Price Chart Illustrates Performance Cost of Reusability,” *Space News*, May 2, 2016, <http://spacenews.com/spacexs-new-price-chart-illustrates-performance-cost-of-reusability>.

89 Nathan Daniels, “Current Space Launch Vehicles Used by the United States,” (Washington, DC: American Security Project, April 2014), <https://www.americansecurityproject.org/wp-content/uploads/2014/05/218841132-Current-Space-Launch-Vehicles-Used-by-the-United-States.pdf>.

relative to the Delta IV, for example.⁹⁰ But skepticism about the higher possible savings is warranted, especially in light of the dramatically exaggerated savings that have been promised in previous eras of rocket modernization, as with the Expendable Launch Vehicle of the 1990s. Indeed, a net cost reduction of 25 percent would be perhaps a more realistic (and still impressive, if attained) goal for the foreseeable future.⁹¹

Where there has been significant progress in space technology to date, it has largely been in making payloads themselves smaller through the use of miniaturized satellites. In recent years, this trend has been particularly significant in commercial and civilian markets, in functional areas such as communications for remote areas of the planet, low-resolution Earth observation, and weather forecasting.⁹² Militaries can greatly benefit from these developments as well, for example in creating more resilient communications networks less vulnerable to a small number of anti-satellite weapon attacks against large individual platforms. In addition, the proliferation of small Earth-observation satellites allows more continuous tracking of larger objects on Earth (such as North Korean long-range missiles).⁹³ For example, the company “Planet” operates a fleet of nearly 200 small satellites, in the 5-kilogram range, with roughly 3-meter resolution, and some 30 ground stations to receive data. This fleet of satellites is able to map the entire surface of the Earth daily, taking more than 1 million images from its constellation. Large-data analytics can then compare the same regions from day to day to look for militarily significant changes.⁹⁴ Certainly these trends, offshoots of the computer and robotics revolutions, will continue into the future.

Missile defenses are also improving, though gradually. Consider first kinetic or “hit-to-kill” technology. Systems using an interceptor to destroy a threatening payload from a missile launch have become fairly reliable against short-range and intermediate-range ballistic missiles in the midcourse parts of their flight trajectories. To date, longer-range systems are getting better, but less dramatically. The U.S. midcourse system, with interceptors based in Alaska and California, has finally achieved its first true intercept against a long-range missile. It has an overall test record of about 50 percent success, though most tests have been against shorter-range simulated threats.⁹⁵ Further progress is expected. With expected improvements to the kill vehicle, and to sensor networks including the Sea-Based X-Band Radar and Long-Range Discrimination Radar, midcourse missile defense seems likely to achieve reasonably good performance

90 Adam Mann, “Heavy-Lift Rocket Poised to Boost Space Science,” *Science* 359, no. 6374 (January 26, 2018): 376-377.

91 Mike Wall, “SpaceX Rocket Could Be 100-Percent Reusable by 2018, Elon Musk Says,” *Space*, April 10, 2017, www.space.com/36412-spacex-completely-reusable-rocket-elon-musk.html; and Todd Harrison et al., “Implications of Ultra-Low-Cost Access to Space,” (Washington, DC: Center for Strategic and International Studies, March 2017), 5-6, <https://www.csis.org/analysis/implications-ultra-low-cost-access-space>.

92 Lucien Rapp, Victor Dos Santos Paulino, and Adriana Martin, “Satellite Miniaturization,” (Toulouse, France: University of Toulouse, 2015), <http://chaire-sirius.eu/wp-content/uploads/2015/07/Note-SIRIUS-Satellite-Miniaturization.pdf>.

93 David E. Sanger and William J. Broad, “Tiny Satellites from Silicon Valley May Help Track North Korea Missiles,” *The New York Times*, July 6, 2017, <https://www.nytimes.com/2017/07/06/world/asia/pentagon-spy-satellites-north-korea-missiles.html>; and Zachary Keck, “North Korea’s New ICBMs: How Well Can American Intelligence Track Them?” *The National Interest*, August 6, 2017, <http://nationalinterest.org/blog/the-buzz/north-koreas-new-icbms-how-well-can-american-intelligence-21801>.

94 Michael Bold, “Very Small Satellites, Very Big Deal,” *Army ALT Magazine*, January-March 2018, 229-237. Planet had raised almost \$200 million in capital as of early 2018, suggesting individual satellite costs of under \$1 million. See also Robert Draper, “They Are Watching You,” *National Geographic*, February 2018, 41-45.

95 Daniel Wasserbly, “U.S. Homeland Missile Defence System Scores First ICBM Target Intercept,” *Jane’s Defence Weekly*, June 7, 2017, 4; and Thomas Karako, Ian Williams, and Wes Rumbaugh, “Missile Defense 2020: Next Steps for Defending the Homeland,” (Washington, DC: Center for Strategic and International Studies, April 2017), 53-54, 73-78.

capabilities against simple threats in the coming decades.⁹⁶ Other countries may achieve good capabilities, too.⁹⁷

In broad terms, however, while midcourse defenses will improve against a given fixed threat, they still suffer from fundamental limitations that probably make them a mediocre long-term answer to the ballistic missile challenge. Decoys need not be particularly complicated to fool even advanced sensors because they can always mimic the heat and radar cross section of actual warheads. If need be, warheads (and decoys) can even be placed within Mylar balloons to disguise them in the vacuum of space during midcourse flight. This remains as true today as in the great countermeasure debates of earlier decades, since physics has not changed since then.⁹⁸ Moreover, maneuverable warheads are also feasible, particularly for more advanced powers.⁹⁹

Boost-phase defenses should work increasingly well over the next 20 years, particularly against a small coastal country like North Korea, where the United States and allies could station various platforms within close range of plausible launch sites. It is very difficult to do this from space, given the “absentee ratios” of satellites in low-Earth orbit. But airborne drones carrying interceptors or lasers, or interceptors based on ships or land, might be effective in such situations, especially given ongoing progress in laser weapons, as discussed further below.¹⁰⁰

A related topic is anti-satellite weapons. Whatever one’s views about the desirability of limiting these systems, given that many satellites help promote strategic stability, it will be increasingly hard to prevent development of ASATs in the future. It is implausible that a world with many advanced missile defense systems and space-launch capabilities can really avoid creating ASAT potential inadvertently. Indeed, that is already the case today. China, the United States, and Russia have all already either shot down low-Earth orbit satellites in recent years or demonstrated the inherent ability to do so, generally with their missile defense systems. China and Russia have continued to develop various kinds of ASAT capabilities to the extent that the head of U.S. Strategic Command, General John Hyten, has expressed worry about America’s overall competitive position in space.¹⁰¹ In the years ahead, systems that can carry out ASAT roles even in geosynchronous orbit could become more common. Indeed, a maneuvering satellite at such an altitude is already in effect a potential ASAT, since the replacement of its

96 Lori J. Robinson, “Statement before the Senate Armed Services Committee,” (testimony, Senate Armed Services Committee, Washington, DC April 6, 2017), 8-10, <http://www.northcom.mil/Portals/28/NC%202017%20Posture%20Statement%20Final.pdf?ver=2017-04-06-110952-160>; and Thomas Karako, Ian Williams, and Wes Rumbaugh, “Missile Defense 2020,” 93-96.

97 See, for example, Gabriel Dominguez and Neil Gibson, “China Develops ‘Ultra-Fast Interceptor,’” *Jane’s Defence Weekly*, June 7, 2017, 8.

98 Andrew M. Sessler et al., *Countermeasures: A Technical Evaluation of the Operational Effectiveness of the Planned U.S. National Missile Defense System* (Cambridge, MA: Union of Concerned Scientists, 2000); and James M. Lindsay and Michael E. O’Hanlon, *Defending America: The Case for Limited National Missile Defense* (Washington, DC: Brookings Institution Press, 2001), 94-99.

99 “Ballistic and Cruise Missile Threat,” (Wright-Patterson Air Force Base, OH: Defense Intelligence Ballistic Missile Analysis Committee, June 2017), 8, <https://fas.org/irp/threat/missile/bm-2017.pdf>.

100 See, for example, David E. Sanger and William J. Broad, “Downing North Korean Missiles Is Hard. So the U.S. Is Experimenting,” *The New York Times*, November 16, 2017, <https://www.nytimes.com/2017/11/16/us/politics/north-korea-missile-defense-cyber-drones.html>.

101 Gabriel Dominguez, “U.S. Risks Losing Advantage in Space to China and Russia, Warns STRATCOM Chief,” *Jane’s Defence Weekly*, December 13, 2017, 6.

existing payload with explosives could turn it into a space mine with little difficulty.¹⁰² Satellites can try to protect themselves against various types of electronic or directed-energy attacks from standoff distances, to some extent. But in the end, redundancy of satellites seems a more realistic strategy for preserving meaningful access to space than any ban on ASATs or any direct defense against them.

Three more categories in this wide-ranging, quick survey of platform-related technology are surface ships, submarines, and stealthy aircraft. In regards to basic ship technology, the watchword remains evolutionary change, not revolution, especially in terms of hydrodynamics, structural design, efficiency of movement, and speed. Yes, there have been and will be some exotic innovations. Certain newer vessels travel just above the water's surface, as with one variant of the U.S. Navy's Littoral Combat Ship, based partly on innovations associated with the 1991 Fincantieri Destrier vessel. Some employ triple hulls, as with the trimaran variant of the Littoral Combat Ship, or capture their own wakes, as with the lesser-known Stiletto. Otherwise, however, basic physics continues to limit the performance of major vessels, based on the simple fact that drag is a nonlinear function of ship speed, growing faster than speed in proportionate terms.¹⁰³ Today's large warships travel at similar speeds to those of nearly a century ago. No major plans or technologies that would change this basic situation are envisioned for the fleet over the next 20 years (and beyond), it is safe to say.¹⁰⁴ A notional trimaran transport ship that might travel at 55 knots, if successfully developed, would require perhaps four to eight times as much power as today's large transport ships yet carry only one-fourth of the payload. And that is if it even proves possible to develop.¹⁰⁵

Submarine quieting continues to advance, through the classic methods of isolating machinery within a submarine, using anechoic materials on its surface, and further extending "snorkeling time" through air-independent propulsion and related methods. New ideas in submarine quieting involve using low-magnetism steels in the hull, to reduce detectability by magnetic detectors, or placing new coatings on submarines that could absorb or redirect sonar in order to reduce detectability by active sonar. If the Seawolf class of submarines really offered the potential for quieting that was sometimes purported in the unclassified literature—approaching a tenfold improvement in quietness—it seems plausible that such technologies could be engineered to be more economical in the coming years, and thus to be used on more vessels.¹⁰⁶

102 Peter L. Hays, "United States Military Uses of Space: Issues and Challenges," in *Space and Security: Trends and Challenges*, ed. Yoshiaki Sakaguchi (Tokyo: National Institute for Defense Studies, 2016), 23; Massimo Pellegrino and Gerald Stang, "Space Security for Europe," (Paris: EU Institute for Security Studies, July 2016), 24; and Michael E. O'Hanlon, *Neither Star Wars Nor Sanctuary: Constraining the Military Uses of Space* (Washington, DC: Brookings Institution Press, 2004), 61-117.

103 "M80 Stiletto," Naval Technology, 2017, <http://www.naval-technology.com/projects/m80-stiletto>; "Littoral Combat Ship," *Naval Technology*, 2017, <http://www.naval-technology.com/projects/littoral>; and Milan Vego, "No Need for High Speed," *Proceedings*, (September 2009): 46-50, <https://usnwc2.usnwc.edu/getattachment/fd318cca-90c7-4221-8f3f-946e8ec07e05/VEGO-NO-NEED-FOR-HIGH-SPEED-PROCEEDINGS-SEPT-2009.aspx>.

104 Michael O'Hanlon, *Technological Change and the Future of Warfare*, 80; and "Destroyers - DDG," U.S. Navy, 2017, http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=900&ct=4.

105 David Arthur, "Options for Strategic Military Transportation Systems," (Washington, DC: Congressional Budget Office, September 2005), 27, <https://www.cbo.gov/sites/default/files/109th-congress-2005-2006/reports/09-27-strategicmobility.pdf>.

106 Julian E. Barnes, "A Russian Ghost Submarine, Its U.S. Pursuers and a Deadly New Cold War," *The Wall Street Journal*, October 20, 2017, <https://www.wsj.com/articles/a-russian-ghost-submarine-its-u-s-pursuers-and-a-deadly-new-cold-war-1508509841>; and William Herkewitz, "This Camouflage Coating Hides Submarines from Sonar," *Popular Mechanics*, March 27, 2015, www.popularmechanics.com/military/navy-ships/news/a14800/this-camouflage-coating-hides-submarines-from-sonar.

Regarding aircraft stealth, some important new concepts and approaches are in the works. Shapes of key parts of aircraft, such as intakes to engines and exhaust vents, continue to be refined, as drawings of the B-21 bomber suggest, for example. (The B-21, expected to have a radar cross section between that of a “metal bumblebee” and a golf ball, will not be supersonic, however, since the shape needed to make it stealthy is incompatible with stable high-velocity flight.¹⁰⁷) Materials that can attenuate returns from lower-frequency radars (which do better at finding most types of stealthy aircraft, at the price of being less accurate) are being investigated. They include so-called “metamaterials,” composite artificial materials assembled from various types of constituent elements like metals and plastics.¹⁰⁸ Electronic countermeasures that can cancel out radar returns from stealthy aircraft are also evolving and improving. Materials that are less inclined to degradation or to heating (which produces a potentially detectable infrared signature) are being researched, too.¹⁰⁹

What are the likely trends in the competition between submarines and anti-submarine warfare, as well as the net trend in the stealth-counterstealth competition over the next couple decades?¹¹⁰ I would hazard the following broad and rough prognostications based on current capabilities and expected developments. In many water conditions and locations, the submarine probably can be said to enjoy a certain basic advantage over sensors that future trends in technology will be hard-pressed to alter. Quantum computing, in some minds, offers the potential to find the submarine’s wake like a needle in a haystack, through sustained monitoring and analysis of ocean surface conditions. This seems incredulous under all but the most benign sea conditions. Sensors would have to survive enemy attempts at interruption; submarines would have to maintain a steady course and not avail themselves of countermeasures; sea conditions would probably have to be very calm such that the random effects of wind, waves, and other objects in the water on surface conditions do not camouflage the submarine signature. And for those able to pay for stealthy aircraft, such planes will likely continue to have the edge over radar systems and other sensors trying to find and track them. At the same time, the sensor technology is improving fast enough that this could be an interesting competition to watch.

OTHER TECHNOLOGIES

Finally, there is a category of miscellaneous technologies that deserve mention. They range from nonlethal weapons of various kinds, to biological pathogens and other weapons of mass destruction, to lasers and particle beams, to rail guns and long-range kinetic strike systems, to enabling technologies such as nanomaterials and additive printing or 3D manufacturing.

Start with non-lethal weapons. Most of the concepts recommended as feasible and deployable even 20 years ago, such as a cable to incapacitate ship propellers, slippery substances to make passage on bridges difficult, and acoustic weapons to disable enemy foot soldiers, appear not to have received significant attention or resources in the first two decades of the 21st century. There was some success in the 1999 Kosovo War in initially

107 Jerry Hendrix and James Price, “Higher, Heavier, Farther, and Now Undetectable?” (Washington, DC: Center for a New American Security, June 2017), 54-55, <https://www.cnas.org/publications/reports/higher-heavier-farther-and-now-undetectable>.

108 Duncan Brown, “Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar,” 8-9.

109 Kris Osborn, “The U.S. Air Force Is Doing All It Can to Keep the B-2 Bomber Stealth,” *The National Interest*, June 6, 2017, <http://nationalinterest.org/blog/the-buzz/the-us-air-force-doing-all-it-can-keep-the-b-2-bomber-21020>.

110 Dan Katz, “Shaping Things to Come,” *Aviation Week and Space Technology*, September 18-October 1, 2017, 64-67.

using graphite filament ordnance rather than explosives to disable electricity in Belgrade, and there have been a few other isolated examples of success as well—but not many.¹¹¹

As the wars of the 21st century have demonstrated to date, lethal ordnance remains the coin of the realm for almost all tactical settings.¹¹² Whether it is stopping a suspicious truck that might contain a bomb, incapacitating a shooter immersed within a civilian crowd, or creating a perimeter around a protected asset into which potential threats cannot be allowed access, lethal weaponry is still the default mechanism by which American forces and their allies and friends protect themselves.

There is some reason to think that could change considerably in coming years, however. For example, solid-state laser technology is coming of age and becoming deployable and affordable. Soon, mobile lasers may be able to disperse crowds, incapacitate a given individual in a crowd, or disable a given vehicle, without a high risk of fatalities.¹¹³

Solid-state lasers can soon be expected to be capable of damaging or destroying many threatening systems on the tactical battlefield, in fact. However, some of the most promising applications may be in maritime domains, for the short-range defense of ships. Aircraft may also use them for protection against threatening missiles.¹¹⁴ One such system, known as the Self-protect High-Energy Laser Demonstrator (SHIELD) is to be prototyped by 2021 according to current plans.¹¹⁵ Ground vehicles will surely use them against artillery, mortars, UAVs, and other proximate threats. In recent years, successful tests have been conducted against mortars and quadcopters, for example.¹¹⁶ A key test is scheduled for 2022 with the High-Energy Laser Mobile Test Truck (involving a 100-kilowatt laser).¹¹⁷ It is important to remember, however, the inherent limitations of such weapons even when they become available, in terms of range, power, number of kills per minute, and restrictions during bad weather.¹¹⁸

Consider next weapons of mass destruction. Most chemical and nuclear weapons technologies are fairly mature and evolving only modestly if at all. The Chemical Weapons Convention has limited research on chemical agents. Recent reports by the U.S. intelligence community focus their sections on weapons of mass destruction on the use of sarin by the Syrian government, on violations of the Intermediate-Range Nuclear Forces

111 See, for example, Richard L. Garwin, *Nonlethal Technologies: Progress and Prospects* (New York: Council on Foreign Relations, 1999), 1-31; Benjamin S. Lambeth, *NATO's Air War for Kosovo: A Strategic and Operational Assessment* (Santa Monica, CA: RAND, 2001), 42; and Ivo H. Daalder and Michael E. O'Hanlon, *Winning Ugly: NATO's War to Save Kosovo* (Washington, DC: Brookings Institution Press, 2000), 145.

112 Dan Lamothe, "The U.S. Military Has Pain Rays and Stun Guns. So Why Aren't They Being Used?" *The Week*, August 7, 2014, <http://theweek.com/articles/445332/military-pain-rays-stun-guns-why-arent-being-used>.

113 David Hambling, "Raytheon's New Radar Tech Could Realize the Pentagon's Pain Ray," *Popular Mechanics*, April 4, 2016, www.popularmechanics.com/military/research/a20264/raytheons-gallium-nitride.

114 Aaron Mehta, "Inside the 'Foundational' Future Technologies of the World's Largest Defense Company," *Defense News*, October 19, 2017, <https://www.c4isrnet.com/show-reporter/ausa/2017/10/19/inside-the-foundational-future-technologies-of-the-worlds-largest-defense-company>; Doug Cameron, "Pentagon Makes New Push to Put a Laser Weapon on a Fighter Jet," *The Wall Street Journal*, December 8, 2017, www.wsj.com/articles/pentagon-makes-new-push-to-put-a-laser-weapon-on-a-fighter-jet-1512756505; and Kris Osborn, "Navy Develops Laser Weapon Prototypes for Destroyers, Cruisers—maybe Carriers," *Scout*, April 2, 2017, www.scout.com/military/warrior/story/1625939-navy-accelerates-warship-fired-laser-weapons.

115 Valerie Insinna, "Coming in 2021: A Laser Weapon for Fighter Jets," *Defense News*, November 7, 2017, <https://www.defensenews.com/air/2017/11/07/coming-in-2021-a-laser-weapon-for-fighter-jets>.

116 Michael Holthe, "Precision Fires Tilt the Field," *Army ALT Magazine*, January-March 2018, 64-72.

117 Graham Warwick, "High-Energy Laser Weapons," *Aviation Week and Space Technology*, December 25, 2017-January 14, 2018, 77; and Kip R. Kendrick, "When Beams Combine," *Army ALT Magazine*, January-March 2018, 70.

118 Duncan Brown, "Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar," 14-15.

Treaty by Russia, and on modernization of Chinese ballistic missiles and submarines. Underlying research on new chemical technologies are not generally the major subjects of attention.¹¹⁹ Even the Russian nerve agent Novichok used in the horrific 2018 attack on the Soviet double agent living in Britain was invented more than a quarter-century ago.¹²⁰ The main exception to this assertion may be in the new category of drugs including opioids, fentanyl, and carfentanyl—which behave in many ways like advanced chemical weapons, and could be employed that way in war.

The Nuclear Test Ban Treaty, though never ratified, has nonetheless been respected by the major nuclear powers since the 1990s and thereby impeded fundamental new work on nuclear explosives. Much nuclear research in the United States since then has gone into stewardship of the existing arsenal.¹²¹ Much academic and scholarly writing about the bomb has emphasized nonproliferation, arms control, and disarmament rather than technical advancement.¹²² Where some evolution has occurred, regrettably, has been in the sophistication of trade networks that have helped proliferators to access key technologies to build weapons in places such as Pakistan and North Korea.¹²³

There was a flurry of interest in biological weapons after the 2001 anthrax attacks in the United States. But since then, public policy has focused more on naturally occurring biological pathogens, most notably Ebola, rather than on the development of biological warfare agents or protective capabilities.¹²⁴ To be sure, Ebola itself could be used as a weapon in the future, particularly by terrorist groups, though there is considerable debate as to how effective any such effort would likely be.¹²⁵

The future may bring more radical changes, and graver dangers, in biological weaponry. The core technical fundamentals for revolutionary developments are in place: in understanding and synthesizing DNA into viruses and other potential pathogens, and also in the ongoing difficulty of verifying compliance with the Biological Weapons Convention's prohibition on the research and development of pathogens.¹²⁶

119 Daniel R. Coats, "Worldwide Threat Assessment of the U.S. Intelligence Community," (testimony, Senate Select Committee on Intelligence, Washington, DC, May 11, 2017), <https://www.dni.gov/files/documents/Newsroom/Testimonies/SSCI%20Unclassified%20SFR%20-%20Final.pdf>.

120 See, for example, Will Englund, "What a Brave Russian Scientist Told Me about Novichok, the Nerve Agent Identified in the Spy Attack," *The Washington Post*, March 12, 2018, https://www.washingtonpost.com/news/worldviews/wp/2018/03/12/what-is-novichok-the-russian-nerve-agent-and-the-scientist-who-revealed-it/?utm_term=.f7a478ed98b7.

121 Stephen M. Younger, *The Bomb: A New History* (New York: Harper-Collins Publishers, 2009); and James E. Doyle, *Renewing America's Nuclear Arsenal: Options for the 21st Century* (London: International Institute for Strategic Studies, 2017), 24-28, 82-83.

122 Richard L. Garwin and Georges Charpak, *Megawatts and Megatons: A Turning Point in the Nuclear Age?* (New York: Alfred A. Knopf, 2001); Harold A. Feiveson, et al., *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation* (Cambridge, MA: MIT Press, 2014); and Arnie Heller, "Stockpile Stewardship at 20 Years," (Livermore, CA: Lawrence Livermore National Laboratory, 2015), <https://str.llnl.gov/july-2015/verdon>.

123 Robert Einhorn, "Non-Proliferation Challenges Facing the Trump Administration," (Washington, DC: Brookings Institution, 2017), vi.

124 It is striking how many of the review articles on biological weapons and warfare turned up by standard searches were written in the last years of the 20th century or 2001 and 2002. There has generally been much less literature since, it would appear. See for example, "Overview of Potential Agents of Biological Terrorism," Southern Illinois University, 2017, <https://www.siumed.edu/im/overview-potential-agents-biological-terrorism.html>; and John B. Foley, "A Nation Unprepared: Bioterrorism and Pandemic Response," *Interagency Journal* 8, no. 2 (2017): 25-33.

125 Stephen Hummel, "Ebola: Not an Effective Biological Weapon for Terrorists," *CTC Sentinel* 7, no. 9 (September 29, 2014): 16-19, www.ctc.usma.edu/posts/ebola-not-an-effective-biological-weapon-for-terrorists.

126 Kai Kupferschmidt, "Labmade Smallpox Is Possible, Study Shows," *Science* 357, no. 6347 (July 14, 2017), <http://science.sciencemag.org/content/357/6347/115>; John D. Steinbruner, *Principles of Global Security* (Washington, DC: Brookings Institution Press, 2000), 175-193; and C. Raina MacIntyre, "Biopreparedness in the Age of Genetically Engineered Pathogens and Open Access Science: An Urgent Need for a Paradigm Shift," *Military Medicine* 180, no. 9 (September 2015), <https://www.ncbi.nlm.nih.gov/pubmed/26327545>.

Consider several more technologies. Rail guns are making considerable strides.¹²⁷ They may soon replace traditional guns on some major ships. For example, they could extend direct-fire ranges of shipborne weapons to 100 miles or more, with round velocities at least twice that of traditional chemical-propelled ordnance.¹²⁸

High-powered microwaves have some promise. However, uncertainties about whether they have successfully destroyed the electronics of a given enemy system, combined with inherently limited range (given that their power falls off inversely with the square of the distance from the weapon to its target), may limit their future roles unless the terminal defenses protecting a given asset can be reliably penetrated.¹²⁹

Human performance enhancements of various types are sure to improve by 2040. Various types of exoskeletons show the ability to increase power of given limbs or joints, or to reduce the metabolic energy consumption required to create a certain amount of force or torque, by 25 percent or more.¹³⁰ Relatively safe medications like Modafinil can keep people awake and at a high level of performance for up to two days; even more powerful and relatively safe medications seem likely to emerge over the next two decades.¹³¹ These kinds of changes seem likely to happen in the competitive domain of warfare, whatever reservations a country like the United States may have had about them in the abstract. That said, it remains unclear how much difference they will really make if combatants on all sides of a given conflict all have access to relatively comparable performance enhancers. Nor will any of the foreseeable advances make comic book heroes out of soldiers. People may run 1 or 2 miles per hour faster, stay awake a day longer, or lift 50 percent more weight. They will not learn to fly or leap tall buildings.

One more type of relevant technology is additive manufacturing, or 3D printing. It will be useful to militaries, to be sure. For example, it will help considerably in remote logistics operations, reducing the number of spare parts and other metallic or ceramic or related supplies that could be needed, but would be difficult and costly to preposition.¹³² It is less obvious that additive manufacturing will revolutionize most other areas of defense manufacturing.¹³³ And even on the battlefield, it will not change the fact that fuel, food, and water will still need to be transported in massive amounts to deployed troops. So its likely effects on logistics operations, while important, may reduce supply requirements by 10 to 20 percent, not 50 to 75 percent. Still, especially when combined with improvements in battery, fuel cell, and solar systems, some noticeable reductions in battlefield logistical footprints may become possible.¹³⁴

127 Andrea Shalal, "U.S. Military Sees More Use of Laser, Microwave Weapons," *Reuters*, July 28, 2015, <https://www.reuters.com/article/us-usa-military-arms/u-s-military-sees-more-use-of-laser-microwave-weapons-idUSKCNQ22HH20150728>.

128 Geoff Fein, "U.S. Navy Recharges Railgun Development Effort," *Jane's Defence Weekly*, June 14, 2017, 12; and Ronald O'Rourke, "Navy Lasers, Railgun, and Hypervelocity Projectile: Background and Issues for Congress," (Washington, DC: Congressional Research Service, August 1, 2018), <https://fas.org/sgp/crs/weapons/R44175.pdf>.

129 Duncan Brown, "Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar," 17-21.

130 Juanjuan Zhang et al., "Human-in-the-Loop Optimization of Exoskeleton Assistance During Walking," *Science* 356, no. 6344 (June 23, 2017): 1280-1283.

131 Javier Gonzalez, "Go Pills for Black Shoes?" *Proceedings* 143, no. 7 (July 2017), www.usni.org/print/91128.

132 Argie Sarantinos-Perrin, "A New Dimension of Acquisition," *Army ALT Magazine*, January-March 2017, 83-87.

133 David Rotman, "The 3-D Printer That Could Finally Change Manufacturing," *MIT Technology Review*, April 25, 2017, <https://www.technologyreview.com/s/604088/the-3-d-printer-that-could-finally-change-manufacturing>; Rose Hansen, "A New Composite-Manufacturing Approach Takes Shape," *Science and Technology Review*, June 2017, 16-10; and "Printing Things Everywhere," *The Economist*, July 1, 2017, 15.

134 Duncan Brown, "Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar," 35-38.

In concluding this section, it may be useful to offer a brief word on some new materials that can go into the construction of various weapons platforms. Consider two broad categories—nanomaterials and “bespoke” materials. A recent survey of experts in materials found that so-called bespoke materials, exquisitely designed to have very specific chemical and atomic structures and compositions, are probably not on the horizon as major components of key military systems in a major way before 2040.¹³⁵

Nanomaterials, with dimensions on the order of one-billionth of a meter, are somewhat more significant and promising. They are already in use in some applications. Their promise is greatest in improving the power of explosives, the strength of materials, and the storage capacity of batteries. They may also be useful in manufacturing compounds at the molecular level through nanorobotics techniques. The degree to which they are introduced in widespread applications may be constrained by cost and other challenges associated with manufacturing them in large amounts. But they will likely improve the performance of certain types of capabilities—explosives, body armor, high-performance batteries—by as much as 50 to 100 percent, where cost considerations are not prohibitive.¹³⁶ Indeed, since their invention in 1991, lithium-ion batteries have continued to make rapid strides, and that progress will likely continue, largely as a result of the availability of such materials.¹³⁷

SYNOPSIS

In the 1990s, much of the United States strategic community was breathless about the so-called revolution in military affairs, or RMA. I doubted at the time that a revolution was underway and would conclude today that in fact no broad-brush revolution has occurred since the Cold War ended. Old methods of combat and legacy systems have not been rendered fundamentally obsolete by progress in technology, military organizations, or operational concepts.

However, the RMA may be back. And the revolution may really happen this time. The period of 2020 to 2040 seems likely to experience significantly more change than the previous two decades in the character of warfare. For the period from 2000 to 2020, revolutionary technological change probably occurred only in various aspects of computers and robotics. For the next two decades, those areas will remain fast-moving, and they will be joined by various breakthroughs in artificial intelligence and the use of big data. The battlefield implications in domains such as swarms of robotic systems, usable as both sensors and weapons, may truly come of age. In addition, laser weapons, reusable rockets, hypersonic missiles, rail guns, unmanned submarines, biological pathogens, and nanomaterials may wind up advancing very fast. The sum total may or may not add up to a revolution. But the potential cannot be dismissed.

Moreover, the rise of China and return of Russia supercharge the competition and raise the stakes. The marriage of rapid technological progress with strategic dynamism and hegemonic change could prove especially potent. The return of great-power competition

135 Ibid., 9-10.

136 Bjorn Hogberg, “Remote Control of Nanoscale Devices,” *Science* 359, no. 6373 (January 19, 2018): 279; T. X. Hammes, “The Future of Conflict”; and Duncan Brown, “Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar,” 9-10.

137 Christopher Mims, “The Battery Boost We’ve Been Waiting for is only a Few Years Out,” *The Wall Street Journal*, April 1, 2018, <https://www.wsj.com/articles/the-battery-boost-weve-been-waiting-for-is-only-a-few-years-out-1521374401>; and Robert F. Service, “Lithium-Sulfur Batteries Poised for Leap,” *Science* 359, no. 6380 (March 9, 2018): 1080-1081.

during an era of rapid progress in science and technology could reward innovators, and expose vulnerabilities, much more than has been the case this century to date.

Some areas of military technology—most types of sensors, most types of major vehicles, most underlying technologies for nuclear and chemical weapons of mass destruction—seem unlikely to change dramatically. But perhaps a true military revolution of sorts will occur even without such developments. The key question, as always, will be how these individual technology trends interact synergistically with each other, and how military organizations as well as political leaders innovate to employ them on the battlefield.

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