Science and Technology Planning for the Future—Operating in Three Realms

Chapter Seven

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CHAPTER SEVEN

Science and Technology Planning for the Future—Operating in Three Realms

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The United States does not know where its nation's military may be asked to respond in the future, but *how* it responds is embedded in U.S. strategy, with operational and tactical components based on doctrine, training, and technology. Unlike 20th-century conflicts, this century's doctrine, training, and technology exist in three realms: physical, human, and cyber—the last an abstract realm created by the physical interconnectedness between humans and between humans and machines.[1]

Developing offensive and defensive technology for warfare in the physical realm has been vital for millennia. To control a populace, subjugate it, or ultimately force its surrender still requires action in the physical realm.

Controlling a populace's will—the human realm—without direct force has also existed for millennia. Intimidation and propaganda affect the human character, not the human corpus. Therefore, sociology and psychology have always functioned as an intimate accessory to force.

The advent of internet technologies in the 1990s, which gave rise to the cyber realm, combined with more recent advances in data analytics has revealed even more insight into human behavior.

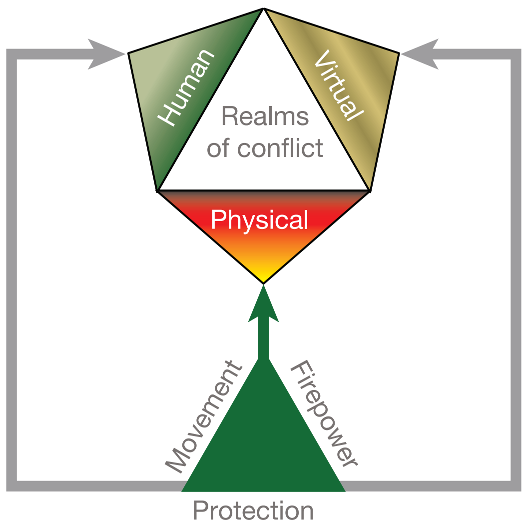
As the cyber realm has evolved since 2000, the links between the physical and social sciences have grown stronger. In the cyber realm, one can manipulate people and systems from afar. Vulnerabilities in computer code can be exploited to impede physical systems—and human susceptibility to rumors can be exploited to impede discourse. The cyber realm amplifies propaganda's ability to bypass critical thinking and elicit emotional responses.

The U.S. Department of Defense (DoD) is attempting to understand how its military can operate in the human and cyber realms with the same facility as it does in the physical realm. See Figure 7.1. Consider a future combined arms operation in which the cyber realm is used to prepare a battlespace—using online rumors to disrupt a populace and crowd avenues of

[1] Joseph N. Mait, *A Report on Army Science Planning and Strategy*, Adelphi, Md.: Army Research Laboratory, 2013; Joseph N. Mait, *A Report on Army Science Planning and Strategy*, Adelphi, Md.: Army Research Laboratory, 2014.

FIGURE 7.1

The Three Realms of Future Conflict



SOURCE: Mait, 2014. Original graphic courtesy of COL (ret) J. P. Buche, U.S. Army Special Assistant to the Defense Advanced Research Projects Agency (DARPA) director, 2011–2014.
NOTE: This graphic originated with DARPA in the 2010s and introduced the *virtual* domain of competition, which has subsequently been reimagined as the *cyber* domain.

ingress and egress, thereby impeding adversarial military movement. This might be followed by mobile robots performing cavalry surveillance and security in front of mounted artillery supported by infantry dismounts. How this robotic- and cyber-enhanced military force maneuvers, attacks, feints, and (if necessary) retreats effectively using all three realms is still under development.

Creating science and technology (S&T) programs that depend on sociology and psychology is different than creating S&T programs for the physical sciences. The social sciences are less reductionist than the physical sciences; there are no immutable physical laws, such as conservation of energy. Instead, a multiplicity of factors must be examined. The essential features of the human-social and cyber realms are interaction and interconnectedness on a massive scale. How does one structure S&T research programs in these areas?

This chapter is the first of several that address questions of aligning and managing S&T research across physical and social science disciplines. It introduces the reader to DoD's S&T enterprise, which is based predominantly on the physical sciences; draws distinctions between the physical and social sciences that affect how their research is conducted; and provides guidelines for structuring social science programs to meet the needs of decisionmaking and engagement in undergoverned spaces (UGS). *UGS* are those spaces in which a state presence is weak and legitimate institutions fail to exist.

The subsequent chapters in this part of the report—by Andrew M. Parker,[2] Elisa Jayne Bienenstock,[3] and Edward Geist[4]—address specific scientific challenges, while Chapters Eleven, Twelve, and Thirteen (by Steven W. Popper,[5] Paul K. Davis,[6] and Robert J. Lempert, Kelly Klima, and Sara Turner,[7] respectively) in the next part take on the connection between scientific knowledge and decisionmaking. These chapters address the importance of social science to national security, the importance of having a strategic posture, and how to support the development of technology based on social science in an enterprise dominated by the physical and computational sciences.

The observations in this chapter are drawn from my experience as chief scientist of the Army Research Laboratory (ARL) developing programs grounded in the physical sciences. The presentation is personal, not academic. This is meant both to illuminate the mindset of a physical scientist and to make the process of developing technology tangible to readers unfamiliar with it. I draw particularly from research efforts on autonomous agents to highlight the interplay between the physical, human, and cyber realms. I present the features of a well-structured physical sciences program and end with comments and caveats on applying these features to programs that encompass all three realms.

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[2] Andrew M. Parker, "The Need to Invest in Social Science Infrastructure to Address Emerging Crises," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022.

[3] Elisa Jayne Bienenstock, "Operationalizing Social Science for National Security," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022.

[4] Edward Geist, "Why Reasoning Under Uncertainty Is Hard for Both Machines and People—and an Approach to Address the Problem," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022.

[5] Steven W. Popper, "Designing a Robust Decision–Based National Security Policy Process: Strategic Choices for Uncertain Times," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022.

[6] Paul K. Davis, "Toward an Analytic Architecture to Aid Adaptive Strategy for Competing in Undergoverned Spaces," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022.

[7] Robert J. Lempert, Kelly Klima, and Sara Turner, "Multi-Stakeholder Research and Analysis for Collective Action in Undergoverned Spaces," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022.

The Research Structure in the Physical Sciences

The tangible tools we use in our daily lives are based on scientific principles that matured into engineering before being mass manufactured into useful implements. This progression from science to engineering to technology, often ascribed to Vannevar Bush, is reflected in the government's budgetary categorization of research (see Table 7.1).[8] However, despite my linear presentation here, readers should not conclude that the progression itself is also linear. This perception persists because applications appear only at the end of the technology development process.

Each stage is distinguished by an increase in understanding, which is obtained by posing different questions. But what is the origin of these questions?

As represented in Table 7.2, different sources are possible depending on motivation.[9] The table categorizes research according to two different (although possibly complementary) goals—to increase fundamental understanding and to provide utility through application. In the upper right quadrant, known as *Pasteur's Quadrant*, applications motivate the questions posed. Most research supported by and performed in agencies throughout the federal government resides in this quadrant. In DoD, it is the unmet needs in security and defense capabilities that drive science to engineering and ultimately to technology.

In the following sections, the differences between science, engineering, and technology are defined and distinguished by the different research motivations indicated in Table 7.2.

TABLE 7.1

Department of Defense Research, Development, Test, and Evaluation Budget Activity Codes and Descriptions

Code	Description
6.1	Basic Research
6.2	Applied Research
6.3	Advanced Technology Development
6.4	Advanced Component Development and Prototypes
6.5	System Development and Demonstration
6.6	RDT&E Management Support
6.7	Operational System Development
6.8	Software and Digital Technology Pilot Programs

NOTE: RDT&E = research, development, test, and evaluation.

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[8] John F. Sargent, Jr., *Department of Defense Research, Development, Test, and Evaluation (RDT&E): Appropriations Structure*, Washington, D.C.: Congressional Research Service, R44711, October 7, 2020.

[9] Donald E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation,* Washington, D.C.: Brookings Institution Press, 1997.

TABLE 7.2
Research Types

		Consideration of Use	
		Low	High
Quest for Understanding	High	Basic research	Application-driven basic research
	Low	(Combination does not exist)	Applied research

Defining Differences Among Science, Engineering, and Technology

The *Oxford Dictionary* defines *science* as "the systematic study of the structure and behavior of the physical and natural world through observation and experiment." Science is driven by observation and a desire to understand observed patterns. Stated simply, science is about understanding the physical world to answer the question "why." Why does the world function in the manner we observe it?

Engineering is defined as "the application of scientific principles to design structures, machines, apparatus, or processes." Unlike science, the operative engineering question is "how." How can an effect be reproduced, and under what conditions? How can one use a physical effect to do something useful?

Finally, *technology* is defined as "the application of scientific knowledge for practical purposes." Technology provides the means to do work based on the scientific and engineering understanding gained. Technology allows one to produce the desired outcome predictably, effectively, and reliably on a large scale.

Distinguishing Types of Research

Understanding the distinctions between science, engineering, and technology is important when attempting to understand different types of research. As noted earlier, Table 7.2 categorizes research according to two goals: increasing fundamental understanding and providing utility through application.

The lower left quadrant, in which research provides no utility and no understanding, is easily dismissed as an unworthy pursuit. The lower right quadrant—applied research—is the *Edisonian Quadrant*. As evidenced by Thomas Edison's approach to develop a viable filament for his incandescent bulb, it is possible to provide utility without fundamental understanding. Rather than ask which properties of materials are the best indicator of their suitability as a filament, Edison chose to test thousands of materials. His inefficient but dogged approach eventually led to a carbonized bamboo filament and the infamous quote "genius is one percent inspiration and ninety-nine percent perspiration." Given limited funds, such a scattershot approach is not well suited for DoD purposes.

We can contrast Edison's approach with that of Albert Einstein's iconic *Gedankenexperiments*, which are representative of the upper left quadrant—*basic research*. Einstein is often portrayed as a lone individual pondering innumerable what-ifs. How else could someone develop a model of gravity as mass bending space or figure out that space contracts and time expands as an object's velocity approaches the speed of light? However, although Einstein's concepts expanded our understanding of the physical world to an unrivaled degree, their utility at the time was uncertain.

Such research is termed *curiosity driven*, and the case for government support of it has always been the unknowns about the long term. No one could have imagined in the early 20th century that Einstein's theory of relativity would prompt a necessary correction to the Global Positioning System[10] or that Einstein's unease with quantum mechanics would prompt the so-called second quantum revolution based on entangled elementary particles.[11]

Referring to the upper right quadrant as *Pasteur's Quadrant* acknowledges that Louis Pasteur's work in chemistry and microbiology was motivated by his desire both for understanding—comprehending the causes of diseases—and application—how to prevent those diseases. The next section discusses examples of how thinking in Pasteur's Quadrant leads to new research and increased understanding.

Examples of Pasteur's Quadrant for Applications of Autonomous Agents

To make Pasteur's Quadrant tangible, I present two examples of autonomous agent development that I was responsible for at ARL: (1) a program to enable handheld autonomous platforms and (2) shaping the laboratory's long-term efforts in autonomous agents. The second example provides perspective on S&T planning that satisfies both policymakers and technologists.

Enabling Handheld Autonomous Platforms

ARL has been involved in developing robotic ground vehicles since the mid-1990s and even helped DARPA formulate its 2004 Robotics Grand Challenge. In 2006, I was asked to develop a research program to mature the capabilities of small (handheld) autonomous platforms. The program was called Micro-Autonomous Systems and Technology (MAST).

The fundamental problem in MAST is that solutions to autonomous locomotion and navigation for vehicle-sized platforms provide little insight to enable handheld ones. Specifically, the energy available for mobility is reduced. Computational processing power is also reduced (i.e., in 2006, the computation available in a chip-scale processor capable of fitting on a small platform was insufficient for the platform to sense, process, move, and navigate as robustly as large platforms at that time had demonstrated). Furthermore, the physics of motion—whether crawling or flying—are different for small platforms than they are for large ones.

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[10] Neil Ashby, "Relativity and the Global Positioning System," *Physics Today*, Vol. 55, No. 5, May 1, 2002.

[11] Jonathan P. Dowling, and Gerard J. Milburn, "Quantum Technology: The Second Quantum Revolution," *Philosophical Transactions of the Royal Society of London,* Series A, *Mathematical, Physical and Engineering Sciences*, Vol. 361, No. 1809, August 15, 2003.

To focus our thinking, my colleagues and I considered the operational challenge of "the last 100 meters."[12] We conceived a mission objective to secure an urban structure using mounted and dismounted troops. Before entering the structure, troops would use small autonomous platforms to enter, map, and explore the building interior while communicating constantly with outside troops.

One problem we recognized in this scenario was how platforms launched in an external environment move into an interior one. For ground crawlers, terrain can change from soil or sand to a hard surface. Flyers must identify points of ingress and fly through them. As they do, aerodynamics can change (e.g., from a breezy exterior to a calm interior). The challenge is for platforms to transition smoothly from one environment to the other. *How* platforms do this became one of MAST's several research foci. This focus eventually led to an increased understanding of terramechanics for crawling platforms, i.e., explaining why large insects walk the way they do, as well as the development of simple parametric models that MAST researchers used to replicate this locomotion on different surfaces.[13]

Shaping the Laboratory's Long-Term Efforts in Autonomous Agents

This MAST example highlights the mindset of scientists and engineers who work in Pasteur's Quadrant. Its specificity indicates the nature of problems this group enjoys solving. Understanding this was helpful when, as chief scientist, I was tasked with developing a long-term research vision to enable the future capabilities desired by the Army for autonomous agents.[14] The program had to be scientifically meaningful yet relevant to the Army.

Senior technical staff, both researchers and managers, and I distilled from Army documentation that effective teaming between soldiers and autonomous agents was an essential desired capability. (We chose the term *agents*, as opposed to *robots*, to underscore that not all autonomous agents are mobile. Many exist on computing platforms, such as agents that are digital assistants on smartphones and smart speakers.)

Through internal and external workshops, we identified three broad areas for investigation: (1) increasing the intelligence of autonomous agents, (2) training humans to work effectively with autonomous agents, and (3) understanding the nature of information exchange and transactions across the human-agent boundary. The first two areas evolved naturally from work already being pursued in the laboratory. However, identifying information

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[12] Daniel W. Beekman, Joseph N. Mait, and Thomas L. Doligalski, "Micro Autonomous Systems and Technology at the Army Research Laboratory," in *2008 IEEE National Aerospace and Electronics Conference*, Dayton, Ohio, 2008; Joseph N. Mait, "The Army Research Laboratory's Program on Micro-Autonomous Systems and Technology," in Thomas George, M. Saif Islam, and Achyut K. Dutta, eds., *Micro- and Nanotechnology Sensors, Systems, and Applications*, Vol. 7318, Orlando, Fla.: SPIE, 2009.

[13] Yang Ding, Nick Gravish, Chen Li, Ryan D. Maladen, Nicole Mazouchova, Sarah S. Sharpe, Paul B. Umbanhowar, and Daniel I. Goldman, "Comparative Studies Reveal Principles of Movement on and Within Granular Media," in Stephen Childress, Anette Hosoi, William W. Schultz, and Jane Wang, eds., *Natural Locomotion in Fluids and on Surfaces*, New York: Springer, 2012.

[14] Army Research Laboratory, "Essential Research Programs," webpage, undated.

exchange across the human-agent boundary spawned new research endeavors to meld information theory and human psychology.

This application of the Pasteur's Quadrant paradigm allowed ARL to structure its efforts objectively, identify metrics for technical performance, and, finally, develop an execution plan despite having only a vague understanding of each area. This structure satisfied the technical staff's attraction to technically deep questions while also meeting the Army's desires. Furthermore, the plan enabled the lab to focus its existing resources and to plan for future ones. Managers were able to identify the disciplines and backgrounds most needed in new hires, identify equipment purchases, and reallocate space.

Structuring Programs for New Realms

The previous section describes the processes I used to craft a focused research program and a strategic vision for long-term research. More important for the purpose of this report are the lessons learned and advice I can offer to those charged with crafting research programs that link psychology, sociology, and other social sciences with physical and information sciences.

Despite the differences between the social and physical sciences, many of my recommendations are repeated in other chapters in this report. A recurrent theme is that the significance of a program is highest when the program is established within the framework of a strategic vision. Establishing a strategic vision bounds the area of investigation and allows one to identify areas where knowledge is high and (more importantly) areas in which knowledge is low and further investigation is required.

A significant difference between the social and physical sciences is that, although each seeks predictive power, the contingent nature of the social sciences places stronger demands on explanation and causal inference. Unlike problems in the physical realm, problems in the human and cyber realms resist simplification to behavior about some equilibrium point. They are nonlocal (entities do not need to be near one another to influence each other), nonstationary (entities' behavior can change temporally in unpredictable ways), and nonlinear (the response of an entity to a change in an input stimulus is not proportional to the change in the stimulus—"the straw that broke the camel's back"). Predicting the behavior of entities in such an environment is less deterministic than doing so for engineered physical systems.

This does not negate the importance of social science research. Rather, it dictates a different mindset toward the research goals, objectives, implications, and applications. As Elisa Jayne Bienenstock emphasizes in Chapter Nine, the lack of immutable physical laws does not relegate social sciences to a lesser field of study. The social sciences still adhere to the scientific method and are just as rigorous as the physical sciences. They have simply adapted science to the character of their discipline.[15]

[15] Bienenstock, 2022.

Characteristics of a Successful Research Program

Successful research and development programs reflect the following factors:

- an understanding of the capabilities desired through meaningful objective metrics
- a balanced portfolio of approaches to achieve the desired capabilities
- the use of transparent and auditable processes in decisionmaking, such as periodic review (especially by knowledgeable outsiders)
- experimentation
- maintaining cognizance of activities in the technical community at large.

Most importantly, program leadership must have the integrity to change direction if periodic review indicates that one approach is not meeting expectations or if community cognizance points to an alternate approach that improves performance. The program must be structured from its inception to allow this flexibility. Research and development programs do not fail because their assumptions were not 100 percent correct at the beginning but because they do not pivot in new directions when required.

Problem Statement and Objective Measures

Technical managers need to set research directions now based on their best estimates of what will be needed in the future. Careful examination of the desired capabilities is essential and leads to a firm foundation on which to build. This is the essence of questions 1–3 in the Heilmeier Catechism (HC), which is used extensively at DARPA to establish new programs (see the text box).[16]

Dialogue between technologists and operators is a good first step to enabling researchers to grasp the general capabilities desired. Early in the MAST program, researchers participated in a three-day exchange with the Army's Maneuver Center of Excellence at Fort Ben-

The Heilmeier Catechism

1. What are you trying to do? Articulate your objectives using absolutely no jargon.
2. How is it done today, and what are the limits of current practice?
3. What is new in your approach and why do you think it will be successful?
4. Who cares? If you are successful, what difference will it make?
5. What are the risks?
6. How much will it cost?
7. How long will it take?
8. What are the midterm and final "exams" to check for success?

SOURCE: DARPA, undated.

[16] DARPA, "The Heilmeier Catechism," webpage, undated.

ning.[17] Researchers received training on small-unit building assault (see Figure 7.2) and discussed with platoon leaders how they might use the as-yet-unavailable technology to increase their likelihood of mission success. This understanding influenced the work performed.

Army documentation and workshops with academics and uniformed personnel shaped our Human-Agent Teaming endeavor. In Chapter Eight of this report, Andrew M. Parker[18] acknowledges the need for collaboration across disciplines and proposes elements of a social science infrastructure to achieve this, while Paul K. Davis[19] also notes in Chapter Twelve the need to overcome disciplinary fragmentation to aggregate knowledge in the social sciences in service of policy applications.

As indicated in the Human-Agent Teaming example, notions about what exactly is needed are sometimes vague. Our identifying the information exchange across the human-agent boundary was a key insight. The next step, again consonant with the arguments by Parker

FIGURE 7.2
Training for a Small-Unit Building Assault, November 2008

SOURCE: Photographs courtesy of the author.
NOTE: In these photographs, uniformed Army personnel from the Army Maneuver Center of Excellence (left) are instructing MAST scientists and engineers (right) on the tactics of small-unit building assault.

17 Albert Sciaretta, Joseph N. Mait, Richard Chait, Elizabeth Redden, and Jordan Wilcox, *Assessing Military Benefits of S&T Investments in Micro Autonomous Systems Utilizing a Gedanken Experiment*, Washington, D.C.: National Defense University, Defense Technology Paper, January 1, 2011.

18 See Chapter Eight (Parker, 2022).

19 Davis, 2022.

and Bienenstock,[20] is to define metrics that enable assessment. Again, these two characteristics address HC questions 1–3.

Building on the Human-Agent Teaming example, collaboration—whether between humans or between humans and agents—requires that all participants share a common understanding of their mission, its execution, and the environment and circumstances in which the mission will be executed. How does one know objectively when this has been achieved? What does one measure, and what value or condition indicates that common understanding has occurred? In an operational setting, the speed with which common understanding is achieved is critical. For a tactical mission, a research goal might be to achieve a 70-percent level of common understanding within seconds. Although how one does this remains unknown, the problem has been distilled from a notional capability to an objective measure of performance. (Recall that my perspective is grounded in the physical sciences.)

Balanced Portfolio, Review, and Experimentation

Because the technology or combination of technologies that lead to success are unknown at the outset of a research project, a balanced portfolio of approaches is important in the beginning. Not all approaches will pan out. This uncertainty is reflected in HC questions 5 (understanding risks) and 8 (checking for success through periodic review). The review process should be formal, transparent, and auditable. It is the process by which decisions are made as the program proceeds and involves both peer review of technical matter by the science and engineering community and review of the program by stakeholders and technical managers. Employing external reviewers disinterested in the outcome is critical.

Second to the external reviewer is the internal *Curmudgeon*, who always tells researchers why something will not work or cannot be done. Technical managers need Curmudgeons to explain in detail why they believe what they believe. Sometimes, the Curmudgeons are wrong. However, even if this is so, Curmudgeons force researchers to reexamine their assumptions and to be rigorous in their analyses.

Graybeards are the Curmudgeon's cousins.[21] They are also internal colleagues who bring their expertise and experience to a program. What distinguishes a Graybeard from a Curmudgeon is the diplomacy with which they tell researchers their baby is ugly. A Graybeard will offer solutions, not just the Curmudgeon's critique.

When technology integration is involved, experimentation is essential. Engineers need to put different pieces together to see how they function. Not a single vehicle completed DARPA's first Grand Challenge in 2004. The farthest any vehicle traveled was seven miles. Although the experience was objectively a failure, the development teams learned from it and

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20 See Chapters Eight and Nine (Parker, 2022; Bienenstock, 2022).

21 Acknowledging that the term *graybeard* is not gender neutral, I am unaware of a suitable alternative that carries the same meaning within the scientific community.

five vehicles successfully completed the 132-mile course in the 2005 Grand Challenge. The chapters that follow recognize the need for experimentation even in the social sciences.

The Army's Future Combat System (FCS) is an ignoble example of the need for experimentation.[22] The development of FCS was motivated by the desire to exploit nascent network capabilities.[23] In 2001, the Army teamed with DARPA to develop the FCS as a program of record. At the time, I posited that achieving the threshold capabilities that policymakers desired by integrating immature technologies on ground vehicles would take longer than predicted. My predictions regrettably proved true, and FCS was cancelled in 2009. Had an acquisition structure existed in 2001 that explicitly allowed for experimentation, FCS might have succeeded. Without this, FCS was constantly pressured to meet acquisition milestones required for a program of record.

The need for experimentation was recognized in the organization of Army Futures Command in 2018. Army Futures Command consists of three major subcommands, one of which is Combat Systems.[24] Combat Systems is responsible for developing experiments, demonstrations, and prototypes. I am cautiously optimistic about this development. It bears noting that technologies developed from the FCS impetus have found their way into ground platforms. The capabilities were not far-fetched; they needed time to mature through test and failure.

Returning to the theme of testing, systems built on integrating technologies are weakest at their seams. Consequently, Red Teams are an essential element in experimentation and its simulation cousin, wargaming. Red Teams consist of Curmudgeons intent on breaking things. Because they serve as surrogates for a real adversary, Red Teams are not bound by the rules of fair play. Consequently, they keep developers on their toes.

Tech Watch and Tech Reachback

A program's primary focus is internal—specifically, how to achieve an objective using an approach that is agreed upon through common understanding and well suited to the personnel and facilities available. However, it is important not to lose sight of developments outside one's purview—cognizance of the community or, colloquially, *tech watch*—which is an important adjunct.

Human-Agent Teaming provides an example of the importance of tech watch and, particularly, advancements in artificial neural networks for computing. Before 2010, neural networks had a checkered history. These networks, inspired by human brain activity, are meant

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[22] Joseph N. Mait and Jon G. Grossman, *The Return to Relevancy: The US Army and the Future Combat Systems*, Adelphi, Md.: National Defense University, April 1, 2002; Joseph N. Mait and Jon G. Grossman, "Is Technology Mature Enough for the Future Combat System?" *National Defense Magazine*, September 2002; Joseph N. Mait, "Balancing Technology and Risk in the Future Combat Systems," *Transformational Science and Technology for the Current and Future Force*, Vol. 42, 2006.

[23] Arthur K. Cebrowski and John J. Gartska, "Network-Centric Warfare: Its Origin and Future," *U.S. Naval Institute*, Vol. 124, 1998.

[24] Army Futures Command Task Force, "Army Futures Command," webpage, March 28, 2018.

to label an input pattern correctly through repeated presentation of the pattern and adaptive modification of internal parameters. Neural network architectures developed in spurts from the late 1950s until the mid-1980s. They fell into disfavor in the late 1990s, when the available computing technology severely limited the class of problems they could solve. This changed in the 2000s with the advent of graphical processing units and distributed computing. This new technology enabled the recognition of complex image and visual problems using multiple layers of neural networks.[25]

The explosive growth in artificial neural nets occurred between my formulation of MAST in 2006 and my becoming chief scientist in 2013. Given my exposure to neural networks dating back to the 1980s, I was more Curmudgeon than Graybeard when I expressed my skepticism that they were a useful tool for Human-Agent Teaming. However, junior staff, who were aware of recent developments, convinced me that artificial neural network performance was not a chimera. The application of neural networks to Human-Agent Teaming, therefore, became a major thrust of our work.

Tech watch is one of several hedges against missteps in initial assumptions. It helps mitigate risk. As a hedge to conventional thinking, online tools based on gaming and crowdsourcing provide a way to generate innovative solutions to solve a specific problem. They are less likely to help answer fundamental questions in science. Furthermore, proffered solutions need to be evaluated and curated to separate science fact from science fiction.

The depth of an organization's bench provides an additional hedge for development programs. *Tech reachback* is the entirety of an organization's staff, beyond just the Curmudgeons and Graybeards, whose broad experience and expertise managers can access when confronted with insurmountable problems that demand immediate attention.

The value of a deep bench is evident in the impact that long-term ceramics research at ARL had on delivering transparent armor to the U.S. Army after the 2003 Iraq invasion. While working at the Army's Material Technology Laboratory in Watertown, Massachusetts, in the 1970s, James W. McCauley developed a transparent ceramic, essentially a bulletproof window using ceramic armor technologies.[26] McCauley continued this work after the Material Technology Laboratory was integrated into ARL in 1992, but it remained primarily a research program.[27] This changed after the U.S. incursion into Iraq. Plagued by improvised explosive device attacks, DoD published an urgent universal needs statement for improved vehicle protection. Within a year, more than 4,000 High Mobility Multipurpose Wheeled

[25] Dan Claudiu Cireşan, Ueli Meier, Luca Maria Gambardella, and Jürgen Schmidhuber, "Deep, Big, Simple Neural Nets for Handwritten Digit Recognition," *Neural Computation*, Vol. 22, No. 12, December 2010.

[26] James W. McCauley, "A Simple Model for Aluminum Oxynitride Spinels," *Journal of the American Ceramic Society*, Vol. 61, Nos. 7–8, 1978.

[27] Parimal J. Patel, Gary A. Gilde, Peter G. Dehmer, and James W. McCauley, "Transparent Armor," *AMPTIAC Newsletter*, Vol. 4, No. 3, Fall 2000.

Vehicle add-on armor kits containing transparent armor were delivered to DoD.[28] Although this is an extreme example of reachback, it underscores the benefits of a deep technical bench.

To close this section, I reiterate the program characteristics that increase the likelihood of a successful research program: meaningful objective metrics that reflect an understanding of the capabilities desired, a balanced portfolio to achieve the desired capabilities, transparent and auditable processes in decisionmaking, experimentation, tech watch, tech reachback, and enlightened leadership.

For programs that span the physical, human, and cyber realms, experimentation is perhaps the most valuable of the listed characteristics. Developing theories, performing analysis, and making predictions when physical absolutes are muddled by human foibles is difficult. Therefore, insight and understanding are best gained through experiments and wargames. I continue this speculative posture in the next section, where I comment on efforts to make strategic and operational planning more adaptive and more competitive.

Comments, Cautions, and Caveats on Building Programs for Undergoverned Spaces

Given the intent of this report, one can reasonably question this chapter's role. My presentation has been a personal one based on lessons learned structuring physical science research programs. Furthermore, my experience has been solely in developing operational capabilities for the future Army. This report is about improving strategic and operational security planning to be more adaptive and competitive.

The authors of the following chapters underscore that the aforementioned lessons learned remain valid even when applied to social science research. An important caveat is that one must understand the nature of social science research. Thus, my decision to highlight programs on humans interacting with technology was deliberate. I have an appreciation for the social scientists' perspectives and an understanding of the work they do, which lends credence to my observations in this final section.

To expand the nation's capabilities to engage in so-called infinite contests, DoD is investing in new technologies to compete in UGS.[29] Prospective programs seek to approach infinite contests by maintaining influence in long-term indeterminate stasis between multiple players.[30] This represents a different dynamic than the pursuit of definitive victory characterized by the adversary's military and political defeat in decisive battle (e.g., Desert Storm)

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28 James M. Sands, Parimal J. Patel, Peter G. Dehmer, Alex J. Hsieh, and Mary C. Boyce, "Protecting the Future Force: Transparent Materials Safeguard the Army's Vision," *AMPTIAC Newsletter*, Vol. 8, No. 4, 2004.

29 Michael D. Rettig and Whitney Grespin "The Spaces in Between: Mitigating Threats in Undergoverned Spaces," *Small Wars Journal*, October 17, 2013.

30 James P. Carse, *Finite and Infinite Games*, New York: The Free Press, 1986.

and a return to the long, indeterminate global contests that characterized the Cold War.[31] Although the emerging competition for influence is similar to the defining infinite contest of the second half of the 20th century, future contests are likely to be more complicated by having larger numbers of more-diverse players and shifting alliances.

As stated in U.S. Joint Doctrine Note 2-19, the role of the strategist is "[to] exercise influence over the volatility, manage the uncertainty, simplify the complexity, and resolve the ambiguity, all in terms favorable to the interests of the state and in compliance with policy guidance."[32] Such a formulation matches the objectives of a *finite game*, in which one side wins, the other loses, and ambiguity is eliminated.[33] In contrast, an *infinite contest*, where influence is in constant flux, requires a different approach to vulnerability, uncertainty, complexity, and ambiguity.[34]

The Observe-Orient-Decide-Act (OODA) loop for decisionmaking, developed after the Korean War, epitomizes the Cold War mentality of competition.[35] A new model for decisionmaking was introduced by the Australian Army in 2006. This model acknowledges the increased complexity of the modern world and emphasizes adaptation.[36] The actions in this decisionmaking loop are Act-Sense-Decide-Adapt (ASDA). See Figure 7.3. The ASDA decisionmaking loop subsumes the OODA loop; it does not replace it.

I comment on the second and third elements of the ASDA mode: Sense and Decide. If the goal is sustaining long-term influence, what does one measure as part of the sensing process to know that applying an ASDA decision loop, as opposed to an alternate approach, has improved one's long-term influence? This is critical because building technology is easy only when one knows what the technology is supposed to achieve.

It is also important to recognize the practical constraints of sensing. One needs to understand the measurements that sensors provide over an area, as well as the measurements they *cannot* provide. In information science, the characteristics of this so-called null space are critical to understanding the limitations of information derived from sensor measurements.

Recognizing the existence of the null space is just as critical in the social sciences as it is in the physical sciences. When sensing is sufficiently dense, even when no sensor is capable of measuring some variable in time and space, e.g., energy or pressure, one can interpolate measurements from multiple sensors to obtain an acceptable and reasonable estimate. How

31 Simon Sinek, *The Infinite Game*, New York: Portfolio, 2019.

32 Joint Doctrine Note 2-19, *Strategy*, Washington, D.C.: U.S. Joint Chiefs of Staff, December 10, 2019.

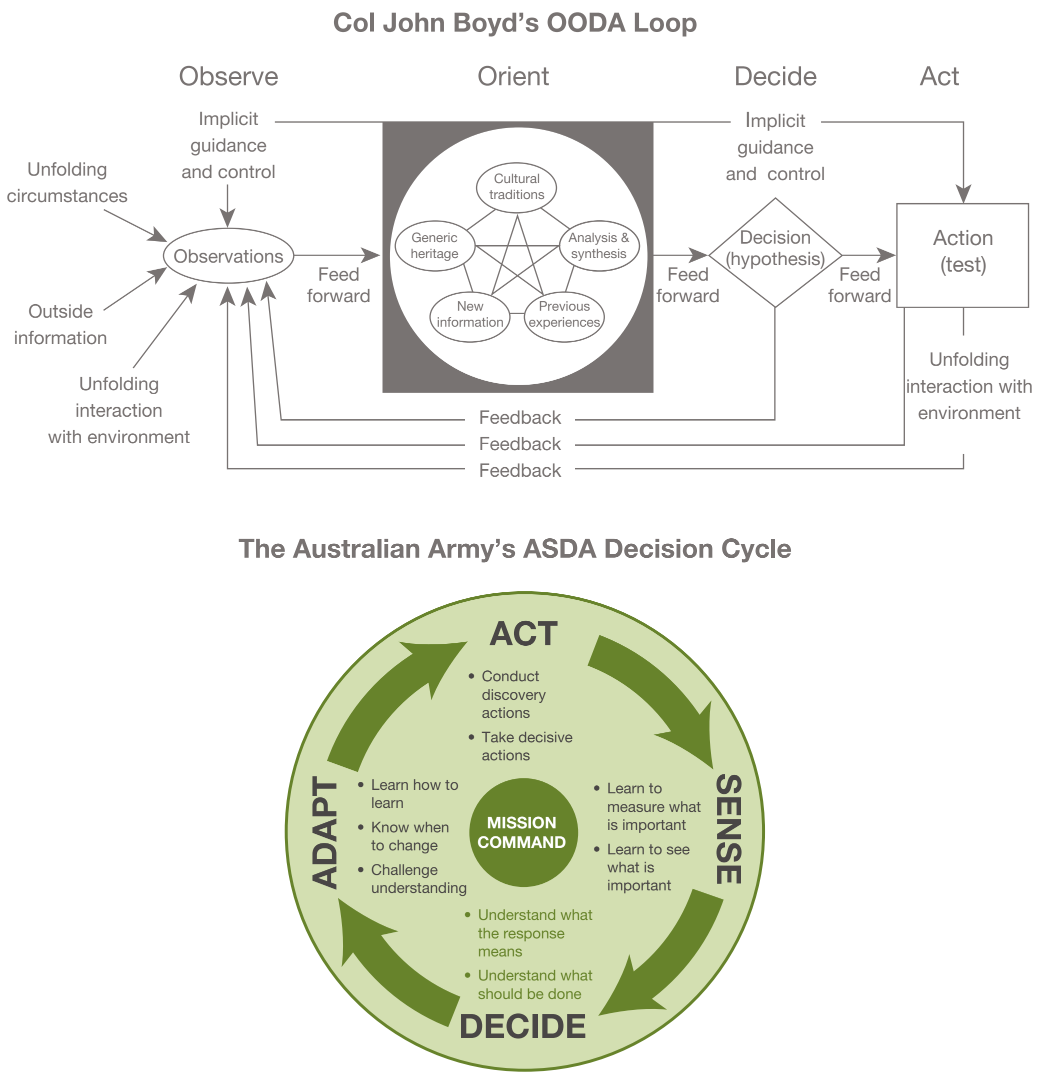
33 Carse, 1986.

34 Nathan Bennett and G. James Lemoine, "What VUCA Really Means for You," *Harvard Business Review*, Vol. 92, Nos. 1–2, February 1, 2014.

35 Robert Coram, *Boyd: The Fighter Pilot Who Changed the Art of War*, New York: Hachette Book Group, 2002.

36 Justin Kelly and Mike Brennan, "OODA Versus ASDA: Metaphors at War," *Australian Army Journal*, Vol. 6, No. 3, Summer 2009.

FIGURE 7.3
Decisionmaking Paradigms



SOURCES: Patrick Edwin Moran, "Diagram of the OODA Loop," Wikipedia, April 19, 2008, CC BY 3.0; Head Modernisation and Strategic Planning—Army, *Army's Future Land Operating Concept*, Canberra, Australia: Australian Army Headquarters, 2009, p. 31. Used with permission.

often one makes measurements and the length of time it takes to process them also affect the fidelity of derived information.

However, all sensors have limitations. Sensing faster or more densely does not overcome the fundamental limitation that there always exist data that cannot be measured. In the physical realm, filling these gaps is called *extrapolation*. In the social realm, filling these gaps is called *speculation*. Both are unreliable and noisy, especially the farther one is from confirmed measurements. In a nonlocal, nonstationary, and nonlinear system, one does not have to be too far away before noise overwhelms any signal.

The period between measurements impacts the effectiveness of decisions based on those measurements. If the period is too long, one can miss important events. However, if it is too short, it is difficult to distinguish a significant event from a random one. Because information is contained in deviations from a norm, it is important to establish a baseline by observing over a long period or, as Elisa Jayne Bienenstock refers to it, measuring the mundane.[37]

One impetus for increased interest in the social sciences is the recognition that many of the problems posed by UGS must ultimately be understood and shaped through the lens of human interaction. A second impetus for increased interest in the social sciences is that advances in computation enable new tools for discovering the inner workings of complex social systems.[38] For example, data analytics have allowed us to discern previously undetectable patterns within a population over time and space and, thus, identify precursors to conflict or crisis. Thus, much effort is focused on the application of these tools to improve decisionmaking.

This is both a blessing and a curse. As alluded to by Bienenstock, the tantalizing potential of such tools creates considerable churn in program executive offices as empirical approaches are generated without the foundational sciences to back them up.[39] The guidance offered in the succeeding chapters, if heeded, provides a hedge against this continual churn.

The programs Bienenstock discusses, however, are not without merit. Their Edisonian approach enables the development of a social science infrastructure, including personnel with the requisite technical skills and a technology base of information.

Concluding Thoughts

Structuring research programs for the future is complicated by the increased melding of elements from the physical, human, and cyber realms. Sociology and psychology have become as important to the nation's safety, security, and defense as the physical and information sciences, largely because of increased people-to-people and people-to-things connectivity. Unlike fields of science with physical laws, a reductionist approach—focusing on a single factor—to multidisciplinary social sciences research is limiting and nearsighted.

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[37] See Chapter Nine (Bienenstock, 2022).

[38] For example, see Chapter Sixteen of this report (Robert L. Axtell, "Short-Term Opportunities, Medium-Run Bottlenecks, and Long-Time Barriers to Progress in the Evolution of an Agent-Based Social Science," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022).

[39] See Chapter Nine (Bienenstock, 2022).

Several factors can help structure research in the social sciences. Experimentation and wargaming are especially useful for testing theories and for measuring the performance of different elements for technologies based on assumptions of human behavior. It is also important for researchers to remain cognizant of developments outside the main technology thrusts of their programs. Without question, integrity and flexibility in program leadership are essential to increasing the likelihood of success of any research program in any field.

Nonetheless, the goal of research remains the same: to gain understanding through scientific study and to use that understanding to engineer systems and ultimately solve problems. Research and development demand objective measures to show an improvement or an advantage over current solutions. The value of an approach derives from the objective outcomes that result from its application and from the conclusions drawn therefrom. The conclusions must stand up to rigorous interrogation and review.

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Abbreviations

ARL	Army Research Laboratory
ASDA	Act-Sense-Decide-Adapt
DARPA	Defense Advanced Research Projects Agency
DoD	U.S. Department of Defense
FCS	Future Combat System
HC	Heilmeier Catechism
MAST	Micro-Autonomous Systems and Technology
OODA	Observe-Orient-Decide-Act
S&T	science and technology
UGS	undergoverned spaces

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