The DARPA Model for Transformative Technologies

Perspectives on the U.S. Defense Advanced Research Projects Agency

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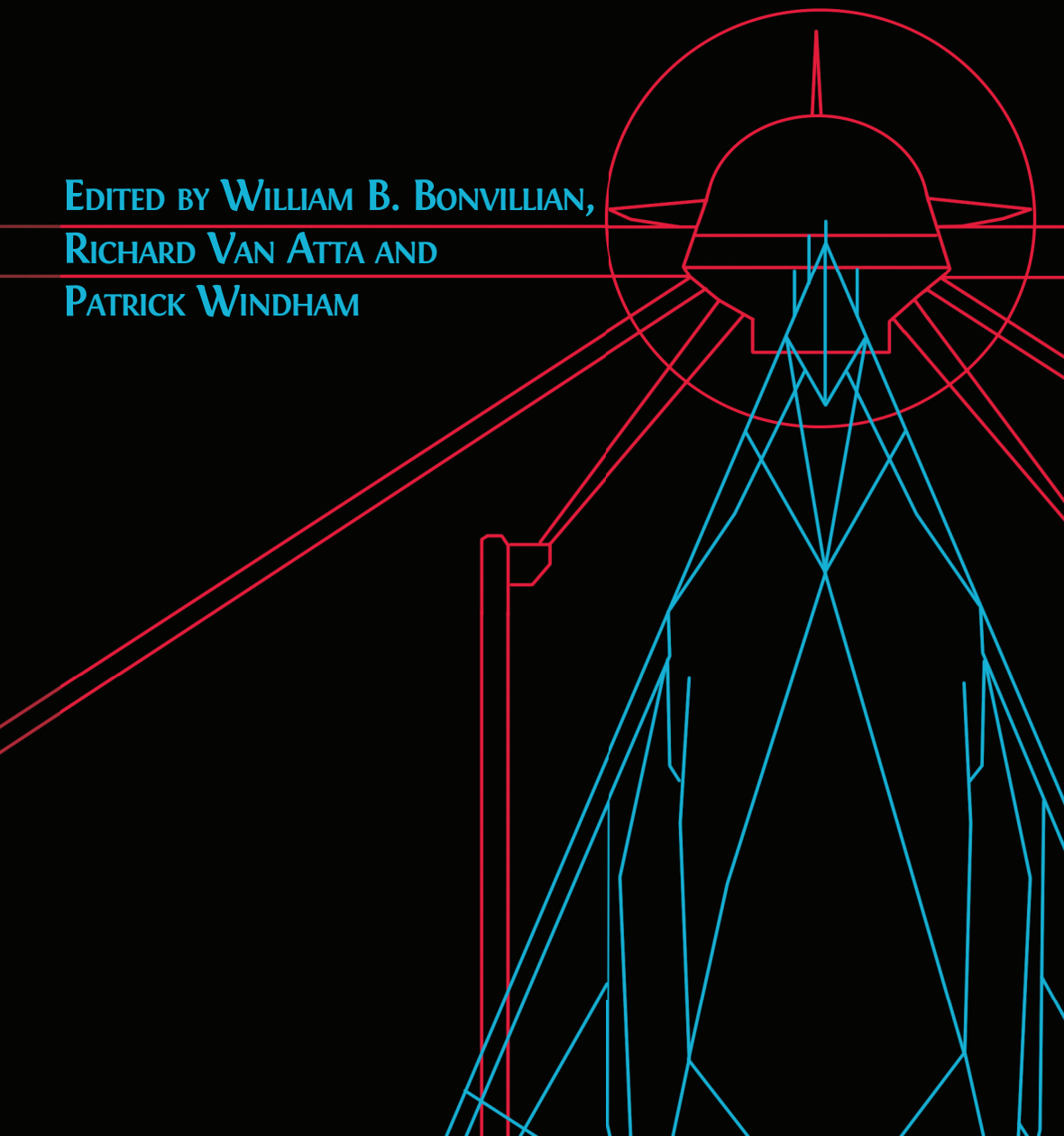

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1. Introduction

DARPA—The Innovation Icon

Patrick Windham and Richard Van Atta

The Defense Advanced Research Projects Agency (DARPA) has become an "innovation icon," widely recognized for playing an important role in the creation and demonstration of many new breakthrough ("disruptive") technologies. Some of these technologies have strictly military applications, such as stealth and precision-guided munitions. Others are "dual-use technologies" that have benefited both the civilian world and the Department of Defense. Examples of these technologies include the Internet, Global Positioning System (GPS) receivers, voice recognition software, advanced semiconductor manufacturing processes, and un-manned aerial vehicles. It is a remarkable record.

This introductory chapter focuses on DARPA's key features—its mission, organization, linkages to other organizations, and "political design"—and how those features have contributed to its success. Later chapters and the book's Conclusion suggest some lessons that DARPA's experience offers for those interested in how this organization has worked over nearly sixty years and for those seeking to create similar technology agencies.

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DARPA's Historical Mission and Organization

DARPA's Evolution

DARPA has existed for over sixty years and during that time it has evolved, changed, and, on a couple of occasions, come close to being dissolved. It has changed in its organizational structure and in some important operational mechanisms as well. There is no simple singular depiction of DARPA that is accurate because it has changed and adapted based on how the world around it has changed—especially on how the national security environment has changed, but also on what different Presidents and their Administrations have asked of it.

Importantly, even at a given point in time there are what might be termed several DARPAs, as different parts of the organization—as small as it is—have focused on very different things—both technologically and in terms of how they function. This is evident from its early history, as Richard Van Atta outlines:

> Indeed DARPA has morphed several times. DARPA has "re-grouped" iteratively—often after its greatest "successes". The first such occasion was soon after its establishment, with the spinning off of its space programs into NASA. This resulted in about half of the then ARPA personnel either leaving to form the new space agency, or returning to a military service organization to pursue military-specific space programs. A few years later, then DDR&E John S. Foster required ARPA to transition its second largest inaugural program—the DEFENDER missile defense program—to the Army, much to the consternation of some key managers within ARPA. Also early in its history ARPA was tasked to conduct a program of applied research in support of the military effort in Viet Nam.[1]

Thus, even by the early 1960s one could say there were three, perhaps four key DARPA thrusts—with the addition of its exploration of new, emerging technologies, such as materials, and the nascent information technologies. As the overview below shows, DARPA's history has been perturbed by political dynamics as well as the dynamics of the technologies it has pursued. Perhaps the most important hallmark of

1 Van Atta, R. (2008). "Fifty Years of Innovation and Discovery", in *DARPA, 50 Years of Bridging the Gap*, ed. C. Oldham, A. E. Lopez, R. Carpenter, I. Kalhikina, and M. J. Tully. Arlington, VA: DARPA. 20–29, at 25, https://issuu.com/faircountmedia/docs/darpa50 (Chapter 2 in this volume).

DARPA has been its adaptability and flexibility to respond to changing circumstances—often extremely rapidly.

DARPA's Origins: 1958–1970

In October 1957, the Soviet Union launched the first artificial satellite, Sputnik I, an accomplishment that shocked the United States. Many Americans worried that the country was losing technological leadership to its Cold War adversary.

After the launch of Sputnik, President Dwight Eisenhower followed the advice of Secretary of Defense Neil McElroy and leading scientists, including his science advisors, James Killian and then Dr. George Kistiakowsky, and proposed the creation of what became the Advanced Research Projects Agency (ARPA). ARPA was formed just four months after Sputnik on 7 February 1958 through DOD Directive 5105.15 by Secretary McElroy.[2] Herbert York, a Manhattan Project veteran and the first director of the Lawrence Livermore Laboratory, helped guide the early evolution of ARPA as its first Chief Scientist and then as the Defense Department's first Director of Research and Engineering.

Initially, the agency focused on three key assignments from the President: space, missile defense, and the detection of nuclear weapons tests. Eisenhower subsequently made it clear that space was to be the realm of a civilian agency, and later, in 1958, Congress and the President created the National Aeronautics and Space Administration (NASA), a civilian agency which took over the country's principal space programs, absorbing much of DARPA's Space Program. The two other Presidential assignments—missile defense and nuclear test detection—continued as the dominant foci for about fifteen years but eventually were moved to other parts of the Department of Defense (DOD).

Also, soon after its founding ARPA took on Project AGILE, as proposed by its Deputy Director, William Godel, which was a decade-long classified program supporting U.S. combat efforts in Vietnam and beyond. In retrospect, much of AGILE was naive, poorly managed and

2 Congress, through an amendment by Senator Mike Mansfield, renamed "ARPA" as "DARPA" in 1972, adding the word "Defense." Congress, through Senator Jeff Bingaman, renamed it "ARPA" again in February 1993, because of its "dual-use" role in creating technologies with commercial as well as military applications. The name reverted to "DARPA" in March 1996.

rife with amateurism. The ARPA Directors had little access or knowledge of what AGILE was doing as Godel "was running the AGILE office as his own covert operations shop".[3] There were important lessons learnt from AGILE (as a program run amok, with little oversight) on what not to do. It was hardly scientific and as an operational program it focused on near-term solutions. It became a key element in defining what DARPA would *not* be in the battle over competing visions for the agency's future.

With the quick transfer of the space program to NASA, ARPA spent the rest of the decade focused on missile defense, nuclear test detection and AGILE. However, in the early 1960s another role for ARPA emerged as it began to pursue a set of smaller, technically-focused programs under the general notion of "preventing technological surprise". Areas initially pursued were materials science, information technology, and behavioral science. In fact, one can argue that ARPA in essence "invented" these as areas of technological pursuit. These began in 1961 under Jack Ruina, the first scientist to direct ARPA, who hired J. C. R. Licklider as the first director of the Information Processing Techniques Office. That office played a vital role in the creation of personal computing and the ARPANET—the basis for the future Internet.

Resuscitation in the 1970s

It is important to note that ARPA in the late 1960s to early 1970s was a troubled agency—a victim of the Vietnam malaise and resource cutbacks that affected all of DOD, and with the additional issue that its post-space program thrusts (missile defense (DEFENDER) and nuclear

3 Weinberger, S. (2017). *The Imagineers of War: The Untold Story of DARPA, The Pentagon Agency That Changed the World*. New York, NY: Alfred A. Knopf, 81. Weinberger goes into considerable detail on Project AGILE and the role of Deputy Director Godel in shaping DARPA's involvement in tactical technologies related to not only U.S. combat in Southeast Asia, but also a much broader focus on counterinsurgency-related activities in other parts of the world. While there were some modestly successful early technology developments under AGILE, such as tactical remotely-piloted vehicles, much of this program was egregiously unsuccessful with harmful repercussions, including Agent Orange and other defoliation efforts, poorly conceived and methodologically suspect social science forays, and the "strategic hamlets" concept of population relocation. Perhaps most damning was the inclination of those running and overseeing these programs, including DARPA's director, to delude themselves that they were effective. Director Charles Herzfeld subsequently stated, "AGILE was an abysmal failure, a glorious failure" (Weinberger. (2017). *The Imagineers of War*, 185).

test detection (VELA)) had essentially run their course. Indeed, as early as 1965, Deputy Secretary of Defense Cyrus Vance, "came to advocate abolishing the Agency".[4] The 1965–1970 era was a crisis period. DARPA evolved both organizationally and programmatically from this crisis largely due to John S. Foster, who became Director of the Defense Research and Engineering (DDR&E)[5] in 1965 and remained for eight years. By the mid-1970s DARPA had jettisoned the AGILE program and transitioned DEFENDER to the Army. DARPA was explicitly looking for new directions first under Director Eberhardt Rechtin, who created a Strategic Technologies Office, and then his successor Steven Lukasik, who saw AGILE as "an embarrassment" and closed it down, transitioning parts of it into a new Tactical Technology Office. Thus, by the mid-1970s DARPA had substantially refocused on technology offices and moved away from the original mission-focused assignments. Crucial to this rejuvenation was DARPA taking on a broad new focus aimed at finding technological alternatives to the use of nuclear weapons to respond to the Soviet Union. This was a key imperative stemming from the concerns of President Richard Nixon and his National Security Advisor, Henry Kissinger, and which continued with Secretary of Defense James R. Schlesinger as a leading proponent under President Gerald Ford. DARPA identified and developed new tactical capabilities based on then emerging technologies through programs on stealth, standoff precision strike, and tactical surveillance via unmanned aerial vehicles (UAVs).

DARPA in the 1980s: Transformative Technology Development and Transition

With this refocusing DARPA survived the axe. Through years of persistent efforts, working with the DDR&E in the Office of the Secretary of Defense (OSD), DARPA transitioned these capabilities to the military,

4 Barber Associates, R. (1975*). The Advanced Research Projects Agency, 1958–1974*. Report Prepared for the Advanced Projects Research Agency, vii-3. Springfield, VA: Defense Technical Information Center.

5 The DDR&E was created in 1958 as the third ranking position in the Pentagon, below only the Secretary and Deputy Secretary of Defense, as essentially the Chief Technology Officer. DARPA reported to the DDR&E. Subsequently this position became the Undersecretary of Defense for Acquisition, Technology and Logistics (USD(AT&L)).

creating what Under Secretary of Defense William Perry and Secretary of Defense Harold Brown (under President Jimmy Carter) would call the "offset strategy"—ways to offset the Soviet Union's conventional war capabilities and lowering the corresponding risk of nuclear war. These key DARPA programs are among the most important programs in terms of the agency's impact on defense capabilities and are often touted as DARPA's impact in ushering in a "revolution in military affairs" evidencing how DARPA helped to transform tactical warfare.

Parallel to DARPA's transformational programs in military technologies in the 1970s-80s were its programs revolutionizing information technology, stemming from the early 1960s focus of IPTO (Information Processing Technology Office) Director Licklider. ARPA/DARPA fundamentally affected what was to become computer science. President John F. Kennedy and Secretary of Defense Robert McNamara became very concerned about a "command and control" communication crisis during the Cuban Missile Crisis; ARPA Director Jack Ruina brought in Licklider to work on it, who saw the problem in a context of evolving computing systems. While one element of this was the ARPANET, this was part of a much broader and increasingly coherent program of research begun under Licklider. His concept of "man-computer symbiosis" provided a multi-pronged development of the technologies underlying the transformation of information processing from clunky, room-filling, inaccessible mainframe machines to the ubiquitous network of interactive and personal computing capabilities.[6] This transformation continues today in DARPA's pursuit of cognitive computing, artificial intelligence and robotics—key DARPA thrusts.

DARPA in the 1990s: End of the Cold War

Early in the 1990s, DARPA, as well as the rest of DOD, had to adapt to the fact that the main adversary, the USSR, had collapsed. Thus, the focus of its weapons research had disappeared. Moreover, the U.S. was in a budget crisis partly due to the vast defense spending of the 1980s. The Clinton Administration entered office with the rubric

6 This transformation is detailed in Waldrop, M. M. (2001). *The Dream Machine: J. C. R. Licklider and the Revolution that Made Computing Personal*. New York, NY: Viking Press.

"dual-use"—technologies that would have both defense and civilian economy payoffs—as one way to make the economy more competitive. Under this approach, DOD could leverage off the civilian sector in cutting costs to develop new technologies. This era of dual-use programs was a major redirection of DARPA and it became highly contentious with elements in Congress. The Technology Reinvestment Project (TRP) was created to partner defense technology developers with commercial firms and universities.

OSD and DARPA worked with the White House to develop this program to continue DARPA's exploration and development of "breakthrough" technologies in the mode of the information revolution, despite the lack of a peer security adversary. Secretary of Defense William Perry emphasized the dual-use concept. During this period emphasis was heavily on fostering new technologies in information and electronics including advanced sensing, while programs in unmanned systems and precision strike continued. Also, programs in biotechnology were started. At the end of the 1990s, DARPA took on a program in partnership with the Army seeking a radical approach for using robotics for ground combat—the Future Combat System—which ultimately proved to be hugely unsuccessful. It was overly ambitious and rushed into acquisition by the Army, and, after the expenditure of about $20 billion, was eventually cancelled by the Secretary of Defense.

DARPA in the 2000s: War on Terror

The 2000s is the period of DARPA Director Anthony Tether—the longest tenured DARPA Director. Within months of taking the role, the terror attacks of September 11 occurred and DARPA became enmeshed in the "War on Terror". The Total Information Awareness (TIA) program became the most notable DARPA response. This became a controversial program as the use of information technologies to identify possible terrorists and terror attacks raised issues of privacy. Tether's tendency to supervise program managers (PMs) also raised questions about whether DARPA should be inherently bottom-up, PM-driven or more director driven. DARPA also developed programs in sensors and sensor systems to support combat needs in Iraq and Afghanistan. During this period DARPA also developed programs in cognitive computing (artificial

intelligence) and autonomous systems with the "DARPA Challenge" contests for self-driving cars as highly visible examples initiating the implementation of these technologies. These Challenges were successful in creating interest and incentivizing teams of researchers to demonstrate integrated autonomous capabilities.

DARPA in the 2010s: Technology for Security in a Globalized World

Through the current decade DARPA has continued on a primarily technology focused agenda in which the emphasis is on pursuing technologies that can create technological surprise. However, it recognized that the world of technology has changed considerably with the advent of globalization. Where the U.S. and DOD led in technology development in the past, now there are global competitors pursuing many of the technologies that DARPA had pioneered. At the same time, there is a growing peer competition in the security arena while terrorism is an ongoing concern. Thus, DARPA's mission of avoiding technological surprise and also creating technological surprise for our adversaries is even more daunting. Under Barack Obama Defense Secretaries Chuck Hagel and Ash Carter, DOD announced a new "Offsets" strategy to attempt to build a new U.S. technological lead as new peer competitors developed capabilities in areas DARPA had created in the previous offset strategy.

DARPA also responded to the era of major advances in life sciences, most visibly, the Human Genome initiatives led by the National Institutes of Health (NIH) and their private sector competitor, J. Craig Venter. DARPA had long been conducting some biotechnology research but in 2013 created a new Biological Technologies Office to focus on this area. Fields like synthetic biology created new kinds of threats that needed counters, and DOD's own massive health care system and injured soldiers from two Middle Eastern wars required new medical responses. While NIH's research remained largely focused on biology, DARPA's flexibility enabled it to pursue a "convergence" approach, creating unified research efforts combining engineering, physical and computational sciences with biology for a new research model pursuing new kinds of therapies. In the information domain, DARPA is focusing on artificial intelligence, cognitive computing, and approaches for

advancing microelectronics to advance quantum computing and neuro-synaptic processors based on how the brain processes information. With a foundation on previous research in aeronautics and propulsion, DARPA is embarking on a major thrust in hypersonic systems. Meanwhile, growing cyber threats spurred several ambitious DARPA programs in cybersecurity.

Thus, the agency's technical and security foci have changed with the times, although its mission has remained largely the same:

> DARPA's original mission, established in 1958, was to prevent technological surprise like the launch of Sputnik, which signaled that the Soviets had beaten the U.S. into space. The mission statement has evolved over time. Today, DARPA's mission is still to prevent technological surprise to the U.S., but also to create technological surprise for our enemies.[7]

However, to carry out this mission today the agency must focus on creating and demonstrating breakthrough technologies for national security, in which there are many more highly capable players and where technologies quickly disseminate globally.

DARPA's Organization and Budget

To achieve its mission of technology leadership DARPA has evolved a highly adaptive and responsive organization. The hallmark of DARPA is agility. At the heart of DARPA are its "technology offices"—the offices where program managers fund the development of new technologies. The agency also has a series of "support offices", which provide services in areas such as contracting, human resources, legal matters, and accelerating the transition of new technologies to the military services. The number of technology offices and their specific roles change over time. Below are the DARPA's current technical offices:

- Biological Technologies Office (BTO)
- Defense Sciences Office (DSO)
- Information Innovation Office (I2O)

7 DARPA. (2005). *DARPA—Bridging the Gap, Powered by Ideas*, 1. Arlington, VA: Defense Advanced Research Projects Agency, http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA433949.

- Microsystems Technology Office (MTO)
- Strategic Technology Office (STO)
- Tactical Technology Office (TTO)

Sometimes DARPA officials and outside observers informally refer to some of these technology offices as "systems offices". In the list above, the two systems offices are the Strategic Technology Office (STO) and the Tactical Technology Office (TTO). These offices create new "proof-of-concept" engineering systems for DOD, such as new unmanned aerial vehicles or small GPS receivers. The goals here are to develop and demonstrate significantly new or improved capabilities and, DARPA hopes, to change people's minds about what is technically possible. The work sponsored by these systems offices is often inspired by long-term national security challenges, needs, or opportunities.

The "systems offices" and the other technology offices typically fund different types of R&D (Research and Development) performers. In the non-systems offices, many of the R&D performers are in universities or component manufacturers. The systems offices usually fund engineering teams that may include defense companies and government laboratories. However, at times the systems offices encounter technical challenges that lead them to also support fundamental research, and the other technology offices sometimes work on military systems. In practice, the line between non-systems technology offices and systems offices is not rigid.

Each DARPA office has multiple "programs" (the term used to refer to R&D funding activities in specific areas of technology). Program managers propose these programs, get approval and funding from senior DARPA officials, write the funding solicitations, select the R&D performers (sometimes with help from other technical reviewers), and supervise and assist the performers. A program manager may supervise several programs. Typically, a program will have specific technical objectives, a budget of tens of millions of dollars, and will last for three to five years. In many cases, an individual program will fund multiple R&D projects run by different performers, so as to test different technical ideas. Having a good set of diverse technical approaches early on in a program is helpful.

Each DARPA technology office also can fund small "seed" programs, which provide a way for program managers to generate and test

new ideas. In recent years, each office also has run an annual "open" competition in which applicants can propose work in areas of technology not covered in the office's programs. These "open" competitions help generate additional new ideas from the technical community.

DARPA therefore uses a "portfolio" approach: it funds a wide range of R&D programs and also often funds multiple projects within a single program. Its program managers are experts who make thoughtful decisions, but since the R&D focus is high-risk to achieve "high payoff" results, the outcomes are unpredictable and the agency and its program managers invest in a range of promising technologies. Some programs and projects will work while others will not. However, by investing in a number of options, the agency seeks to increase the chances of success while accepting the inherent risk that some research may not succeed.

DARPA itself does not build actual operational prototypes of new systems; it turns over "proof-of-concept" prototypes to other parts of the defense and commercial worlds—a process that DARPA calls "technology transition".[8]

At the heart of DARPA are approximately one hundred program managers ("PMs") and the office directors, deputy office directors, agency director and deputy director who supervise them. While these are all government employees, most are hired using special hiring authorities on a term basis—usually of three to five years. Importantly, none of these are permanent staff—all are in essence temporary, although some individuals' tenure may get extended by becoming an office director or deputy director. The agency also has approximately one hundred other government employees who provide important services, such as contracting, legal services, human resources, and security, and at any one time it also has several military liaisons. Additionally, contractors support these government employees. Some of these contractors are highly-trained PhD scientists and engineers who provide valuable technical assistance to program managers, and others are support staff.

The agency's budget for 2019 is $3.427 billion a year. DARPA has no laboratories of its own. It is a funding agency.

8 There was one significant exception. DARPA did develop operational technology for seismic detection of Soviet underground nuclear tests. DARPA was only able to transition this seismic detection network to the Air Force after running it for approximately twenty years.

Important Features of the DARPA Model

DARPA's Focus on Ambitious Goals

Ambitious goals

DARPA focuses on ambitious technological goals, not on incremental improvements.

First, DARPA is a *technology* agency. It funds *advanced research* to develop or create new technologies, not just to explore science. Its mission is to create valuable new technologies. It can support basic scientific research, but as means toward new technology.

Second, DARPA focuses on ambitious, difficult ("DARPA Hard"), and potentially revolutionary projects. It does not focus on immediate or incremental improvements in technology.[9] It focuses on trying to achieve significant changes or shifts in technical capabilities.

Third, DARPA seeks to create "breakthrough", "transformative" or "disruptive technologies"—all terms that are popular today. This means something different than just the creation of novel new devices or tools. Rather, the objective is to create new possibilities and capabilities and particularly seek "change-state" technologies—that is, technologies that significantly change existing capabilities. As a result, the focus is more on outcomes and results rather than the specific character of the technologies that they nurture. So, for example, sometimes an entirely new technology may dramatically improve capabilities. One could argue that the ARPANET was such an example and was a "breakthrough" or "transformative" technology. But at other times integrating existing technologies in new ways may significantly transform capabilities, perhaps by dramatically reducing costs or reducing the time it takes to perform tasks. For example, a new system that significantly reduces the cost and time involved in launching small satellites into orbit may not involve radically new "breakthrough" technologies but rather combine and upgrade existing technologies to create dramatically better capabilities. This

9 There have been times, usually to meet a wartime need, when DARPA has focused on short term technologies, notably under project AGILE during the Vietnam conflict, but these have become exceptions. Under such circumstances, it is important to ask whether DARPA is the best place to pursue such near-term technology developments.

type of improvement is also valuable. Moreover, projects that integrate existing technologies in new ways may carry as much technical risk and offer as much potential benefit as projects to create individual new technologies.

A Challenged-Based R&D Model

DARPA's goals are not only ambitious; they are also focused on specific challenges and opportunities rather than on general discovery or invention. One of this book's editors (William B. Bonvillian) has noted two important aspects of this model: it is "challenge-based", and it is a "connected model" that connects scientific research to these technical challenges.[10]

By "challenge-based", we mean that DARPA program managers identify specific technical capabilities that they think would be both valuable and achievable. Again, DARPA focuses on trying to reach ambitious technical goals but also it tries to demonstrate those capabilities as quickly as possible. It seeks to accelerate the creation of valuable new technologies.

It also uses a "connected model" of R&D—a deliberate process of connecting basic science and engineering to specific technical goals and challenges. This makes DARPA significantly different from some other U.S. R&D agencies. The National Science Foundation (NSF), for example, supports intellectually interesting basic research in universities that is often unconnected to any specific technical goals. NSF funds "pure" research. Practical results may eventually come out of that research, but NSF does not set ambitious technical goals and then create programs designed to achieve those goals. This is not a bad thing. NSF's mission is to advance general knowledge, by drawing upon the talents and curiosity of brilliant researchers. While DARPA draws upon that new knowledge, as well as the skilled researchers that universities train, it nonetheless remains an agency focused on achieving specific technical goals.

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10 Bonvillian, W. B. (2009). "The Connected Science Model for Innovation—The DARPA Model", in *21st Century Innovation Systems for the U.S. and Japan*, ed. S. Nagaoka, M. Kondo, K. Flamm, and C. Wessner. Washington, DC: National Academies Press. 206–37, https://doi.org/10.17226/12194, http://books.nap.edu/openbook.php?record_id=12194&page=206 (Chapter 4 in this volume).

DARPA also sometimes funds basic scientific research itself, if that research is connected to important technical goals. The agency's Defense Sciences Office, for example, funds research in fundamental physics, materials, and mathematics, but mainly for the purpose of helping to advance important capabilities. In this sense, DARPA connects science with technical challenges in ways that it hopes will lead to valuable new technical capabilities.

High-Risk/High-Payoff Projects

DARPA focuses on "high-risk/high-payoff" projects and has developed a philosophy and set of procedures for managing this type of research.

First, the agency is willing to take big technical risks in order to try to get "change-state" results. DARPA is not interested in incremental improvements in technologies or weapons systems. While these improvements are important, especially to the military, they are the province of other R&D agencies. DARPA's specific mission is to develop significant new or better technologies; to do so, it focuses on projects that involve high risk and the possibility of failure but that also will create high payoffs, if successful.

Second, however, there is nothing haphazard or nonchalant about the way in which DARPA takes risks. In fact, one could call its approach one of "thoughtful" or "rigorous" risk-taking. New program managers and office directors are encouraged and expected to fund programs that offer the possibility of significant advances. But they must also think rigorously about whether ambitious goals are achievable and what technical approaches are most promising. Agency leaders expect their program managers to consult widely with relevant technical communities, test and retest their ideas, and constantly learn.

This two-part emphasis on both ambitious goals and rigorous thinking is best seen in a set of questions originally written down by George Heilmeier, a noted inventor and DARPA director from 1975 to 1977. These are questions ("The Heilmeier Catechism") that program managers should ask themselves when designing new programs, and these are the questions that DARPA office directors and the agency director will ask when those program managers propose new initiatives, and when they review these programs:

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

Third, in addition to this overall philosophy, the agency has evolved ways that can help optimize results in this high-risk environment. Here, again, the agency's "portfolio" approach is important. The agency makes thoughtful decisions—which are possible because it recruits world-class experts—in full knowledge that R&D is unpredictable and some programs and projects will fail. Indeed, if none failed, the agency's culture asserts that it would not be doing its job; it would not be bold enough. Investing in a wide range of programs and in a range of projects and technical approaches within those programs increases the chances that the agency's investments will lead to some significant successes as well as some failures.

In addition, DARPA expects that programs and R&D projects within those programs often will not go as planned. These are research projects tackling unknowns and thus it is likely that promising R&D ideas will fail, that new opportunities will be discovered, and therefore that R&D plans need to be adjusted. So, DARPA program managers constantly evaluate projects and work with performers to identify obstacles and opportunities and to make adjustments; DARPA contracts allow them to do this. DARPA does not force its program managers or R&D performers to adhere to unrealistic or ineffective plans or milestones. Projects certainly have technical objectives, but it is expected that R&D projects will change as R&D performers learn what works and what does

not. Program managers and R&D performers themselves continuously evaluate and adapt.

Thus, at DARPA technical failures are expected, since these are high-risk projects and not all will succeed. DARPA and the overall technical community will learn from these dead ends, and the agency will terminate unsuccessful programs and shift funding to more promising ideas. Because the agency has no laboratories or researchers that it must fund year in and year out, it has the freedom to move away from unsuccessful projects to focus on promising ones. Some DARPA leaders state that the only "true failures" occur when R&D performers are unwilling or unable to be candid about the technical problems they are encountering, and therefore the learning process breaks down.[11]

DARPA's Organization and Management

Several of the articles in this compendium identify organizational and management features that have contributed to DARPA's success. These include:

Independence

While DARPA is a DOD agency, under the Secretary of Defense, it has usually had a great deal of independence in determining its overall programs.

However, this does not mean that DARPA does not respond to the national security priorities and strategic directions set by the Secretary of Defense and the President. Recall that ARPA was initially focused on a set of three Presidential issues—areas of national security priority that were identified as being given insufficient focus by the military services. Importantly, these were broad overall research thrusts and ARPA was given wide latitude on how to conduct the research. Generally, this has been the case ever since. This is crucial to DARPA's focus on change-state, revolutionary capabilities: unless a DARPA-type organization is truly independent, then that organization will feel pressure to work on short-term, incremental projects rather than long-term, potentially

11 We are grateful to Dr. Jane Alexander, a former deputy director of DARPA, for making this point.

breakthrough technologies. A related point is that this type of organization can only maintain its independence and budget if it has support and protection from high-level officials.

A Flat, Non-Hierarchical Organization, with Empowered Program Managers

Hiring technically-accomplished program managers and letting them propose and then run R&D programs is a central feature of the DARPA model.[12] Program managers have the authority and responsibility to prepare all the details of a new proposed program: its scope, its rationale (why should we fund it?), the science and engineering behind it, the specific technical objectives, the metrics for measuring technical progress, and the proposed budget and schedule.

Program managers need to be recruited and supervised. DARPA is able to do so using only two layers of management: office directors and their deputies and then the agency director and deputy director. Since these managers are themselves technically very well trained, they can make informed decisions quickly and competently—including which experts to hire as program managers, when to approve or not approve a proposed R&D program, and how to ensure that program managers operate their programs in a technically effective way.

A unique aspect of DARPA's management is that it brings in its key assets—the program managers—on a temporary, short-term basis, usually for three to five years each. Thus, there is roughly a 25 percent turnover every year. Hiring new program managers allows for new ideas and capabilities. But hiring talented program managers can be a challenge, given that private-sector salaries are higher, that the DARPA job only lasts three to five years, and that program managers must move to the Washington, DC, area. However, DARPA also offers exciting opportunities to create new technology, so many people are interested in the possibility of working at the agency. The agency has been able

12 Bonvillian, W. B., and Van Atta, R. (2011). "ARPA-E and DARPA: Applying the DARPA Model to Energy Innovation", *The Journal of Technology Transfer* 36: 469–513 (Chapter 13 in this volume); and Bonvillian, W. B., and Van Atta, R. (2012). *ARPA-E and DARPA: Applying the DARPA Model to Energy Innovation*. Presentation at the Information Technology and Innovation Foundation, Washington, DC, February, https://www.itif.org/files/2012-darpa-arpae-bonvillian-vanatta.pdf

to attract highly capable people who want to work on important and exciting ideas.

Outside Performers and Temporary Project Teams

Research and development are performed entirely by outside performers. DARPA has no internal research laboratory that it must maintain and fund every year and the agency is free to hire whomever it thinks are the best people for specific projects. This emphasizes several key points about the DARPA model: it relies on technically-capable program managers, R&D teams include world-class experts, and the projects DARPA funds are limited in time and focused on specific scientific and technical objectives.

Multi-Generational Technology Investments

If a particular DARPA program is successful, then the agency may fund additional "generations" of three- to five-year programs in this technical area.[13] By working on important technical ideas over longer periods of time, DARPA can create enduring new technologies (technology "motifs") that truly change the technology landscape over time. Each generation of R&D may have different specific objectives and metrics but can be based on a common technical area. Usually each generation learns from prior experience. This may even include supporting a radically different approach to those tried previously, especially if the objective is seen as an enduring national security challenge.

This point about multi-generational investments is important and not always well understood. The fact that DARPA programs typically run from three to five years suggests that the agency funds relatively short-term engineering experiments. It is true that the agency funds many different technical ideas for limited periods of time, but when agency leaders find a new technology that they think offers significant new capabilities for the Defense Department and the country as a whole, they will make sustained investments over many years.

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13 For a fuller discussion of DARPA technology thrust areas, see Van Atta, R., Deitchman, S., and Reed, S. (1991). *DARPA Technical Accomplishments. Volume III.* Alexandria, VA: Institute for Defense Analyses (chapter 4), https://apps.dtic.mil/dtic/tr/fulltext/u2/a241680.pdf

This is usually with a new program manager focused on achieving even more ambitious outcomes, or an entirely new approach, perhaps integrating prior results into a promising new technical idea and creating working prototypes. Technology examples include computing and networking investments, which led to the Internet, iterative advances in artificial intelligence, new concepts for quantum computing and spintronics. On military systems DARPA sponsored many years of investments in stealth, precision-guided munitions, and unmanned aerial vehicles.

Investments in Complementary Strategic Technologies

DARPA sometimes will fund work in additional technical areas relating to major new technology. These related ("complementary") areas are important for the overall success of the new technology, and developing them also builds political support for commercialization and implementation by showing Defense Department leaders and others that the entire system around that new technology will work. For example, DARPA not only invested in early computer routers and the software to run them (the ARPANET) but also in applications of computer networking (file transfers, e-mail, etc.) and later in new computer communications protocols (TCP/IP) that would allow different computer networks to talk to each other. In short, DARPA and its R&D performers created and demonstrated a complete system.

Flexible Hiring and Contracting Authority

The work of DARPA managers and their administrative staff is helped by special laws that apply to DARPA hiring and contracting. For example, DARPA has legal authority to hire program managers very quickly. In the case of program managers from universities or other government agencies, DARPA may use what is called "Intergovernmental Personnel Agreements" (IPAs). Under an IPA, the individual stays an employee of his or her university or laboratory, but he or she is temporarily assigned to DARPA and becomes a temporary government employee under a contract with DARPA. The National Science Foundation and other government R&D agencies also have

this authority. The IPA process allows DARPA to hire quickly and to pay the same salary people earned earlier.

In the case of people from industry, another provision of law (Section 1101 of the Strom Thurmond National Defense Authorization Act for Fiscal Year 1999) allows DARPA to hire experts quickly, although people from industry must leave their companies while they are at DARPA. Congress provided these laws about hiring in part because DARPA program managers are temporary, not permanent federal employees.

All program managers and all senior DARPA managers must follow rules to prevent conflicts of interest—that is, to prevent them from making decisions about whether to award contracts to their current or former employers or to companies in which they own stock. But DARPA has a clear process in which other government employees can make these contract decisions, if the need arises.

In addition to flexible hiring authority, DARPA has legal permission to use a wide range of flexible contracting procedures, including "other transactions authority" (OTA).[14] This OTA power releases DARPA from highly restrictive government procurement requirements. DARPA also has "prize authority". For example, in the robotics field DARPA has sometimes used its legal authority to organize contests and provide prizes, in order to draw in groups that do not usually work with the government.

Creating New Technical Communities

By funding multi-disciplinary teams that both compete and cooperate with each other, DARPA often stimulated new technical communities and new academic fields. Examples over the years include materials science and engineering, computer science, and now synthetic biology/engineering biology. In fact, one can argue that DARPA actually makes two very

14 DOD offers this explanation: "For DOD, 'other transactions' is a term commonly used to refer to the 10 U.S.C. 2371 [Title 10, United States Code, section 2371] authority to enter into transactions other than contracts, grants or cooperative agreements. OTA provides tremendous flexibility since instruments for prototype projects, awarded pursuant to this authority, generally are not subject to federal laws and regulations limited in applicability to procurement contracts." This description is from Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. (2001). *"Other Transactions" (OT) Guide for Prototype Projects*, www.acq.osd.mil/dpap/docs/otguide.doc.

important contributions: it not only helps create and demonstrate new technologies but also helps create important new technical communities.

These researchers then can perform additional R&D, teach students, and contribute further ideas to DARPA. In addition, DARPA-funded communities are a primary means for transitioning the newly-developed technologies to the military and to commercial companies

How DARPA Transfers Its Technologies

DARPA succeeds in large part because other organizations in government and the corporate world further develop and then commercialize and buy the new technologies. In other words, since DARPA itself does not usually build full prototypes or early operational systems, it must rely on other parts of the U.S. national innovation system to perform those tasks. What features of the DARPA model and the overall national innovation system help technology transfer (what DARPA calls "technology transition")?[15]

DARPA's Willingness to Challenge Incumbent Technologies

DARPA is willing to challenge existing technologies and the organizations that produce and use them. Again, the agency sees its job as changing people's minds about what is possible. So, for example, it showed that a computer network using open standards could replace proprietary networking systems. It created and then, with support from the Office of the Secretary of Defense, pushed for the adoption of stealth, unmanned aerial systems, precision strike, and night vision. It uses conferences, prize competitions, "technology insertion projects" (demonstrations of new technology in actual military systems), and other techniques to demonstrate and publicize new technical capabilities.

A Community of Technology Advocates

As discussed earlier, DARPA and its performers create new technical communities. Besides helping DARPA undertake new research,

15 This section draws largely from Bonvillian and Van Atta. (2011). "ARPA-E and DARPA".

researchers in these new communities also often become knowledgeable, enthusiastic advocates for new technologies.

Some of these experts work in the government, some in universities, some for large firms, and some start new entrepreneurial companies. They share an overall vision of what can be done, and they often become what Bonvillian and Van Atta call "communities of change-state advocates"—people who are willing and able to change the technology world. This is a very important reason why DARPA has been so influential.

Close Ties to DOD Leaders

The agency's close ties to Secretaries of Defense and other senior officials not only help DARPA maintain its independence; these ties also mean that these officials become "champions" who want to further develop and then use DARPA-created technologies. Their support is very important for technology transfer. For example, senior DOD officials pushed the U.S. Air Force to adopt both stealth aircraft and unmanned aerial vehicles. Bonvillian and Van Atta see DARPA and DOD using an "island/bridge" model of organization: DARPA is a type of organizational island, with a high degree of autonomy, but it also has a close link ("bridge") to senior DOD officials, helping it to transfer its new technologies to the wider defense world.[16]

Connection to Technically-Sophisticated, Well-Funded Customers

The process of turning a radical new technology into actual products is usually risky, difficult, and expensive. DARPA and the overall Defense Department deal with this difficulty in two ways.

First, DARPA is fortunate that the Defense Department can be both willing and able to turn new prototype technologies into actual products. Its senior leaders may want advanced technologies, and its other laboratories, contractors, and large procurement system can enable the Department to refine and buy these new products. Even so, the "transition" of new technologies from DARPA to the military services is often difficult because DARPA-developed capabilities usually

16 Bonvillian and Van Atta. (2011). "ARPA-E and DARPA", 486.

challenge the current way of doing operations. Thus, DARPA spends considerable time and effort on the transition process, recognizing that it is often difficult.

Second, the agency also works directly with private sector companies that are interested in commercializing new DARPA-demonstrated technologies. One example is DARPA's long work with the semiconductor industry on advanced chip-making technologies which has led to better and less expensive computer chips for both military and civilian customers. Examples includes silicon-on-insulator technology and MMIC signal processing chips. The new commercial frontier of self-driving vehicles is another example of an industry adopting and building upon DARPA-funded research. Many firms and venture capitalists in the commercial world avidly follow DARPA programs.

U.S. intellectual property law helps facilitate this transfer of DARPA-funded technology to the corporate world. Under the Patent and Trademarks Act Amendments of 1980 (popularly known as the "Bayh-Dole Act"), universities and small companies may keep legal title to inventions developed with federal money. When DARPA projects create new technologies, universities may license inventions to companies and small firms can easily use their inventions to help create new products.

A Good Political Design

In addition to the points made above about the way DARPA is organized and how it operates to succeed it must also have a good "political design".[17] Senior government officials, members of the national legislature, and the larger technical community must support the agency or at least not fight its operations and budget. DARPA succeeds because its mission (national defense) is important, because it has a reputation for producing valuable and high-quality technology, and because it does not threaten the budgets of other agencies.

17 Bonvillian, W. B. (2013). *Evolution of U.S. Government Innovation Organization: From the Pipeline Model, to the Connected Model, to the Problem of 'Political Design*. Presentation at the National Graduate Institute for Policy Studies (GRIPS) GRIPS Innovation, Science, and Technology Seminar, Tokyo, April.

The Remainder of this Book

The rest of this book is divided into four parts: Part I, "Perspectives on DARPA"; Part II, "The Roles of DARPA Program Managers"; Part III, "Applying the DARPA Model in Other Situations"; Part IV, "Conclusions".

Part I, "Perspectives on DARPA", has seven chapters. Chapter 2, by Richard Van Atta, is a history of DARPA's first fifty years. Chapter 3, by Michael Piore, Phech Colatat and Elisabeth Beck Reynolds, compares DARPA's culture with more traditional federal R&D agencies, including NSF. Chapter 4, by William B. Bonvillian, discusses the "DARPA Model", and particularly how it follows an approach developed during World War II that connects cutting-edge science with the solution of specific technical challenges. Chapter 5, by Tamara Carleton, discusses the central role of technical vision in DARPA's operations and results. Chapter 6, by Glenn R. Fong, is a history of how DARPA-funded inventions placed a central role in the development of personal computers and their software. Chapter 7, by Erica R. H. Fuchs, discusses DARPA's governance approach as embodying an imbedded network. Chapter 8, by David W. Cheney and Richard Van Atta, explores the processes through which DARPA creates new programs, looking at the origins of several past DARPA programs. Chapter 9, by Patrick Windham, addresses a set of questions that have been raised concerning the DARPA model.

Part II, "The Roles of DARPA Program Managers", contains Chapters 10 and 11, written by Jinendra Ranka and Larry Jackel, two former DARPA program managers.

Part III, "Applying the DARPA Model in Other Situations", contains two chapters. Chapter 12, by William B. Bonvillian, examines the lessons that DARPA's model of creating innovation provides for other, older, "legacy sector" parts of the Department of Defense. Chapter 13, by William B. Bonvillian and Richard Van Atta, discusses how leaders might effectively apply the DARPA model to the (then) relatively new Advanced Research Project Agency-Energy (ARPA-E) as well as organizational lessons from ARPA-E itself. Chapter 14, by William B. Bonvillian, discusses IARPA, another DARPA clone. Chapter 15, by Robert Cook-Deegan, explores the possible application of the DARPA model to the National Institutes of Health (NIH).

Part IV, "Conclusions", consists of Chapter 16, by Richard Van Atta, Patrick Windham and William B. Bonvillian, summarizing key lessons from DARPA's experience on how to structure an organization to successfully create new, innovative technologies.

These various chapters overlap to some degree. However, the editors of this book hope that together they will provide readers with a comprehensive set of insights on how this remarkable government agency works and why it has succeeded as well as it has.

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