The DARPA Model for Transformative Technologies

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

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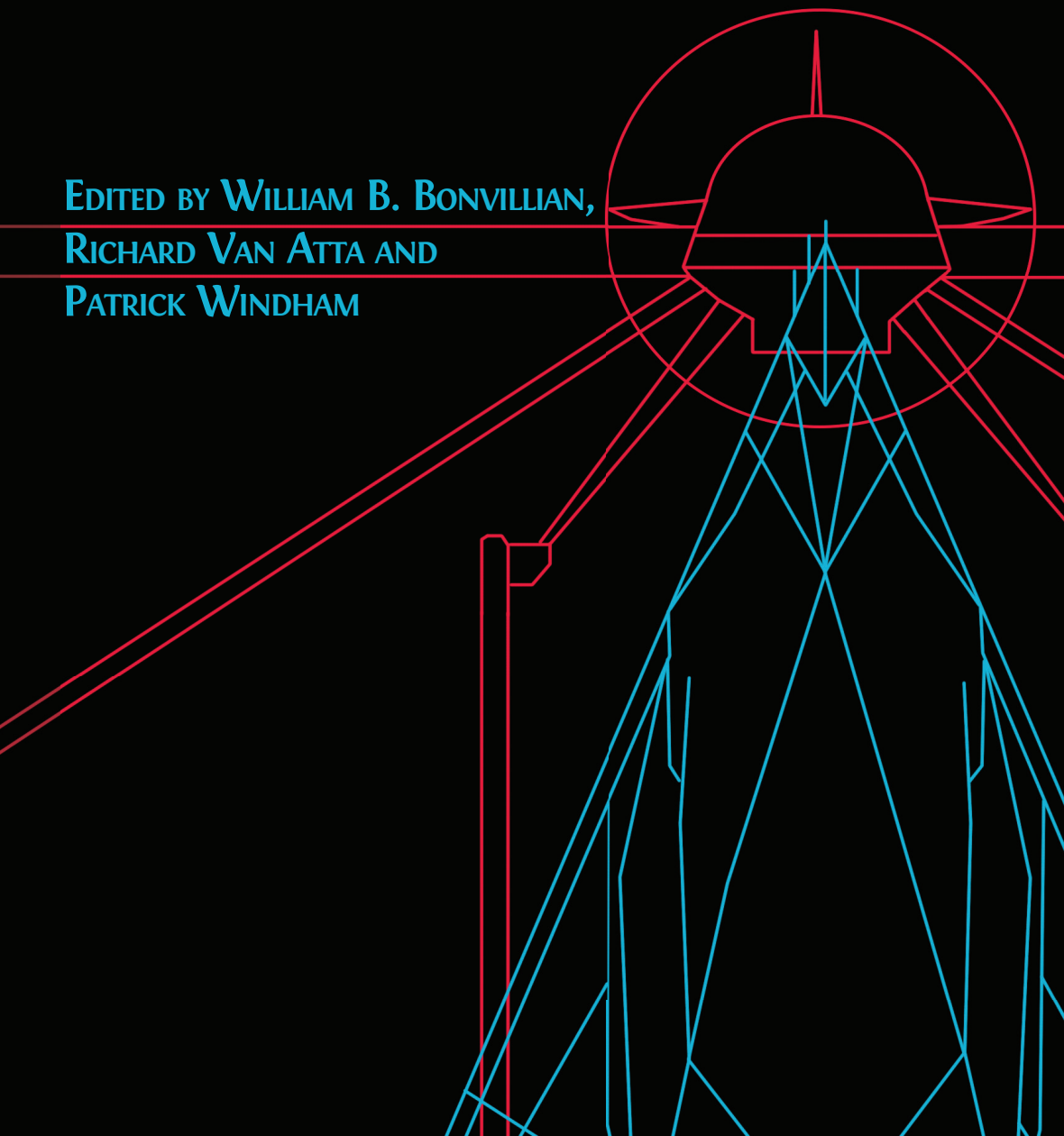

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2. Fifty Years of Innovation and Discovery[1]

Richard Van Atta

The Advanced Research Projects Agency (ARPA)—which came to be known as DARPA in 1972 when its name changed to the Defense Advanced Research Projects Agency—emerged in 1958 as part of a broad reaction to a singular event: the launching by the Soviet Union of the Sputnik satellite on 4 October 1957. While in retrospect, Sputnik itself does not seem to be a particularly significant technological achievement, it had massive psychological and political impact. As recounted in Roger D. Launius' "Sputnik and the Origins of the Space Age", found on the website for NASA's Office of History, "The only appropriate characterization that begins to capture the mood on 5 October involves the use of the word hysteria".[2] Launius wrote in the same document that then Senate Majority Leader Lyndon B. Johnson, recollected, "Now, somehow, in some new way, the sky seemed almost alien. I also remember the profound shock of realizing that it might be possible for another nation to achieve technological superiority over this great country of ours."

1 This contribution originally appeared as a chapter entitled "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, https://issuu.com/faircountmedia/docs/darpa50. This book was published in 2008 to commemorate the agency's fiftieth anniversary.

2 Launius, R. D. "Sputnik and the Origins of the Space Age", *NASA History*, http://history.nasa.gov/sputnik/sputorig.html.

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For the United States to find itself behind the Soviet Union in entering space signified that something was seriously wrong not only with America's space program but with its organization and management of advanced science and technology for national security. Sputnik evidenced that something was substantially wrong with U.S. defense science and technology and that a fundamental change was needed. Out of this ferment—in fact one of the first actions to emerge from it—was a bold new concept for organizing defense advanced research: the Advanced Research Projects Agency. This agency—renamed the Defense Advanced Research Projects Agency (DARPA) in 1972—refocused and rejuvenated America's defense technological capabilities. Moreover, DARPA has also instigated technological innovations that have fundamentally reshaped much of the technological landscape not only in defense capabilities but much more broadly with breakthrough advances in information technologies, sensors, and materials that have pervasive economic and societal benefits.

The "DARPA Model"

DARPA's primary mission is to foster advanced technologies and systems that create "revolutionary" advantages for the U.S. military. Consistent with this mission, DARPA is independent from the military Services and pursues higher-risk research and development (R&D) projects with the aim of achieving higher-payoff results than those obtained from more incremental R&D. Thus, DARPA program managers are encouraged to challenge existing approaches and to seek results rather than just explore ideas. Hence, in addition to supporting technology and component development, DARPA has on funded the integration of large-scale "systems of systems" in order to demonstrate what we call today "disruptive capabilities".

Underlying this "high-risk—high-payoff" motif of DARPA is a set of operational and organizational characteristics including: relatively small size; a lean, non-bureaucratic structure; a focus on potentially change-state technologies; a highly flexible and adaptive research program. We will return to these characteristics later. What is important to understand at the outset is that in contrast to the then existing Defense research environment, ARPA was designed to be manifestly different. It

did not have labs. It did not focus on existing military requirements. It was separate from any other operational or organizational elements. It was explicitly chartered to be different, so it could do fundamentally different things than had been done by the Military Service R&D organizations.

The reason for this dramatic departure, as elaborated below, was that President Dwight D. Eisenhower and his key advisors had determined—as evidenced by the Sputnik debacle—that the existing R&D system had failed to respond to the realities of the emerging national security threat embodied by the Soviet Union.

DARPA's Origins: Strategic Challenges ~1958

Sputnik itself demonstrated that the USSR not only had ambitions in space, but also had developed the wherewithal to launch missiles with nuclear capabilities to strike the continental United States. Therefore, at the outset ARPA was focused initially on three key areas as Presidential Issues: space, missile defense and nuclear test detection.

The first issue, achieving a space presence, was a large element of the initial ARPA, but was spun off to become NASA, based on President Eisenhower's determination that space research should not be directly under the Department of Defense (DOD). According to Herbert York's book, *Making Weapons, Talking Peace: A Physicist's Odyssey from Hiroshima to Geneva*, it was well understood in ARPA that its role in space programs was temporary and that the creation of NASA was already in the works both in the White House and in Congress.[3]

To address ballistic missile defense (BMD), ARPA established the DEFENDER program, which lasted until 1967, performing advanced research relating to BMD and offensive ballistic missile penetration. This program was ARPA's largest over the decade and included pioneering research into large ground-based phased array radar, Over the Horizon (OTH) high-frequency radar, high-energy lasers, and a very high acceleration anti-ballistic missile interceptor, as well as extensive research into atmospheric phenomenology, measurement and imaging, and missile penetration aids.

3 York, H. (1987). *Making Weapons, Talking Peace: A Physicist's Odyssey from Hiroshima to Geneva*. New York, NY: Basic Books, 143.

ARPA's nuclear test detection program, VELA, focused on sensing technologies and their implementation to detect Soviet weapons testing. VELA Hotel satellites successfully developed sensing technology and global background data to detect nuclear explosions taking place in space and the atmosphere, providing monitoring capability supporting the Limited Test Ban Treaty in 1963. VELA also included seismic detection of under-ground explosions and ground-based methods to detect nuclear explosions in the atmosphere and in space.

By 1960, a counter-insurgency project (AGILE) was started as the Vietnam War heated up. This included diverse tactical systems ranging from field-testing experiments leading to the M-16 rifle to foliage-penetrating radar capable of automatically detecting intruders, an acoustically stealthy aircraft for night surveillance, and initial work in night vision.

In 1962 ARPA initiated the Office of Information Processing Techniques and Behavioral Sciences to address information processing "techniques" with a focus on possible relevance to command and control. As is elaborated below, under the expansive vision of its first director, J. C. R. Licklider, this office went on to effect a fundamental revolution in computer technologies, of which the now-famous ARPANET was only one element.

What is DARPA?

DARPA was first established as a research and development organization immediately under the Secretary of Defense with the mission to assure that the U.S. maintains a lead in applying state-of-the-art technology for military capabilities and prevent technological surprise from her adversaries.

ARPA was created to fill a *unique* role, a role which by definition and in its inception put it into contention and competition with the existing Defense R&D establishment. As the Advanced Research Projects Agency, ARPA was differentiated from other organizations by an explicit emphasis on "advanced" research, generally implying a degree of risk greater than more usual research endeavors. As former ARPA Director Dr. Eberhardt Rechtin emphasized, research, as opposed to development, implies unknowns, which in turn imply the possibility

of failure, in the sense that the advanced concept or idea that is being researched may not be achievable. Were the concept achievable with little or no risk of failure, the project would not be a *research* effort, but a *development* effort.

It is clear from DARPA's history that within the scope of this mission the emphasis and interpretation of *advanced* research have varied, particularly in terms of the degree and type of risk and how far to go toward demonstration of application. Risk has several dimensions: (1) lack of knowledge regarding the phenomena or concept itself; (2) lack of knowledge about the applications that might result if the phenomena or concept were understood; (3) inability to gauge the cost of arriving at answers regarding either of these; and (4) difficulty of determining broader operational and cost impacts of adopting the concept. As answers about (1) become clearer through basic research, ideas regarding applications begin to proliferate, as do questions of whether and how to explore their prospects. DARPA is at the forefront of this question and has the difficult job of determining whether enough is known to move toward an application and, if so, how to do so. At times this can be very controversial, as researchers may feel they do not know enough to guarantee success and are concerned that "premature" efforts may in fact create doubts about the utility and feasibility of the area of research, resulting in less funding and (from their perspective) less progress. DARPA, however, has a different imperative than the researcher to strive to see what can be done with the concepts or knowledge, even if it risks exposing what is not known and what its flaws are. This tension is endemic in DARPA's mission and at times has put it at odds with the very research communities that it sponsors.

During times of changing circumstances, the agency has had to reassess its project mix and emphasis due to determinations both internally and within the Office of the Secretary of Defense regarding the appropriate level of risk and the need to demonstrate application potential. In a sense, these somewhat contradictory imperatives serve as the extreme points on a pendulum's swing. As DARPA is pulled toward one of the extremes, often by forces beyond itself, including Congressional pressures, there are countervailing pressures stressing DARPA's unique characteristics to do *militarily relevant advanced research*.

At the other end of the spectrum, as projects demonstrate application potential, DARPA runs into another set of tensions, not with the researcher, but with the potential recipient of the research product. Given that the ideas pursued are innovative, perhaps revolutionary, they imply unknowns to the user in terms of how they will be implemented and how this implementation will affect the implementer's overall operations. To this end, the potential military users seek to reduce their uncertainty in what is a highly risk-intolerant environment by encouraging DARPA, or some other development agency, to carry forward the concept until these risks are minimized, or by simply ignoring, delaying or stretching out its pursuit. While achieving transition can be increased by additional risk reducing research, this also entails substantial additional cost and raises the issue of mission boundaries. Perhaps one of the most critical and difficult aspects of the DARPA Director's job is to decide that DARPA has concluded its part of a particular technology effort and while there is surely more work to be done, it is not DARPA's job to do it.

There have been several occasions in DARPA's history when its management has determined that it has done enough in an area to demonstrate the potential of a specific concept—such as Unmanned Air Vehicles (UAVs)—and that it is thus time for others to fund development of its application and acquisition. These decisions have at times meant that a potential concept becomes a victim of the "valley of death", with the application either failing to be realized, or, as in the case of UAVs, taking over a decade with special high-level attention from the Office of the Secretary of Defense (OSD) to come to fruition

Over the years DARPA has made considerable effort to develop mechanisms to engage potential "customers" in an emerging concept. Working with prospective developers and users as the ideas mature is a key aspect of DARPA project management. However, DARPA has to remain aware that over-extending its involvement in a particular technology development has costs as well—specifically, it means that resources and capabilities are not available to explore other potentially revolutionary ideas. Indeed, this lesson goes back to the very beginnings of DARPA, when it transferred the incipient space program to the newly created NASA. Herbert York, ARPA's first Chief Scientist recalls, that the civilian space program being moved to NASA (and remainder back to the Services) was "what left room for all the other things that ARPA

has subsequently done… including the Internet. If ARPA had been left completely tied up with all these space programs, all kinds of other good things would never have happened".[4]

DARPA's Key Characteristics

It was recognized from the outset that DARPA's unique mission required an organization with unique characteristics. Among the most salient of these are:

- It is independent from Service R&D organizations

DARPA neither supports a Service directly nor does it seek to implement solutions to identified Service requirements. Its purpose is to focus on capabilities that have not been identified in Service R&D and on meeting defense needs that are not defined explicitly as Service requirements. This does not mean that DARPA does not work with the Services, but it does mean that it does not work the requirements that drive Service R&D.

- It is a lean, agile organization with risk-taking culture

DARPA's charter to focus on "high-risk/high-payoff" research requires that it *be tolerant of failure and open to learning*. It has had to learn to manage risk, not avoid it. Because of its charter, it has adopted organizational, management and personnel policies that encourage individual responsibility and initiative, and a high degree of flexibility in program definition. This is one reason that DARPA does not maintain any of its own labs.

A primary aspect of DARPA's lean structure is that it centers on and facilitates the initiative of its program managers. **The DARPA program manager is the technical champion who conceives and owns the program.** As the program manager is the guiding intelligence behind the program, the most important decisions of DARPA's few Office Directors are the selection of and support of risk-taking, idea-driven program managers dedicated to making the technology work.[5]

- It is idea-driven and outcome-oriented

4 York, H. (2007). *Interview*, 5 January.

5 Currently DARPA has Directors for six Offices: Defense Sciences; Information Processing Technology; Information Exploitation; Microsystems Technology; Strategic Technology; and Tactical Technology.

The coin of the realm at DARPA is promising ideas. The Project Manager succeeds by convincing others—the Office Director and the DARPA Director—that he or she has identified a high potential new concept. The gating notion isn't that the idea is well-proven, but that it has high prospects of making a difference. The DARPA program manager will seek out and fund researchers within U.S. defense contractors, private companies, and universities to bring the incipient concept into fruition. Thus, the research is outcome-driven to achieve results toward identified goals, not to pursue science per se. The goals may vary from demonstrating that an idea is technically feasible to providing proof-of-concept for an operational capability. To achieve these results the program manager needs to be open to competing approaches, and be adroit and tough-minded in selecting among these.

Which DARPA?

While the concept of DARPA as a "high-risk—high pay-off" organization has been maintained, it also has been an intrinsically malleable and adaptive organization. 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 (Director of Defense Research and Engineering) 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 Vietnam.

More important than the variety of the programs is that they demonstrate the speed with which DARPA took on a new initiative and also how rapidly its programs can move—sometimes more rapidly than its supporters within DARPA may desire. However, particular programs or technologies have not become the identifier of what DARPA is. Rather, DARPA's identity is defined by its ability to rapidly

take on and assess new ideas and concepts directed at daunting military challenges or overarching application prospects. While the dwell time on new ideas may vary and DARPA may return to the concept iteratively over its history—most notably with its return to missile defense in the 1970s leading to the Strategic Defense Initiative (SDI) in the 1980s—its hallmark is to explore and create new opportunities, not perfect the ideas that it has fostered. A crucial element of what has made DARPA a special, unique institution is its ability to re-invent itself, to adapt, and to avoid becoming wedded to the last problem it tried to solve.

DARPA Roles

Emphasizing DARPA's adaptability is not to say that there are not some underlying elements to what DARPA does. While there have been some additional ad hoc activities thrown in over time, DARPA has had significant roles in the following:

- Turning basic science into emerging technologies
- Exploring "disruptive" capabilities (military and more generic)
- Developing technology strategy into a Defense strategy
- Foster revolution or fundamental transformation in a domain of technology application (e.g., the Internet or standoff precision strike)

Key Elements of DARPA's Success

There are several key elements in DARPA's succeeding in its unique role as an instigator of radical innovation.

- Create surprise; don't just seek to avoid it

DARPA mission is to investigate new emerging technological capabilities that have prospects to create disruptive capabilities. It is differentiated from other R&D organizations by a charter that explicitly emphasizes "high-risk, high payoff" research.

- Build communities of "change-state advocates"

DARPA program managers may often themselves foster a specific concept or technological approach that they seek to explore and develop. But almost never are they the main, let alone sole, investigator of the concept/approach. Rather it is DARPA's motif to instigate cooperation among a group of forward-looking researchers and operational experts. In this sense, DARPA's success depends on it being a leader and catalyst in developing this community of interest.

- Define challenges, develop solution concepts, and demonstrate them

One aspect of DARPA's success has been efforts to define strategic challenges in detail. Since its inaugural Presidential Issues, DARPA has been problem focused, seeking breakthrough, change-state approaches to overcome daunting issues. This has been true in the military realm from the outset. DARPA-sponsored researchers under Project DEFENDER conducted detailed assessments of intercontinental missile phenomena for both defense and offense. For example, in the 1960s and 1970s, DARPA funded studies at the then new Institute for Defense Analyses on missile offense and defense first under the STRAT-X project on ICBM offense-defense followed by then PEN-X study which assessed both U.S. and Soviet capabilities to penetrate missile defense systems. Subsequently, in the late 1970s, DARPA funded studies to understand how the Warsaw Pact was postured against Western Europe in order to determine how technology could provide a means to offset the Warsaw Pact's numerical and geographic advantages. According to *Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs*, a paper by the Institute for Defense Analyses, this planning led to DARPA research in both stealth and standoff precision strike, which provided the basis for Secretary of Defense Harold Brown's and Director of Defense Research and Engineering William Perry's "offset strategy".[6]

Such detailed conceptual work also facilitated DARPA's non-military research—explicitly that in information technology. J. C.

6 Van Atta, R., Lippitz, M., et al. (2003). *Transformation and Transition, DARPA's Role in Fostering a Revolution in Military Affairs. Volume 1.* Alexandria, VA: Institute for Defense Analyses, https://doi.org/10.21236/ada422835, https://fas.org/irp/agency/dod/idarma.pdf

R. Licklider came to DARPA as head of the Information Processing Techniques Office with a vision on man-computer symbiosis that grew in specificity as he collaborated with others, especially Robert Taylor, to present a perspective of internetted computers providing capabilities for collaboration and data interchange amongst researchers.[7] Some of this work is described in Licklider's article, "Man-Computer Symbiosis", and Licklider and Taylor's, "The Computer as a Communications Device".

Tension Between DARPA Roles

DARPA has been a pursuer of new breakthrough technologies *independent of defined needs*. It also has been a developer of concept prototypes and demonstrations that *address needs* (but not defined requirements). While complementary, these are substantially different roles requiring different management approaches and different types of researchers. The first type of endeavor requires an exploratory, somewhat unstructured approach seeking out alternatives amongst competing ideas. The latter focuses on taking a specific set of emerging capabilities and combining them into a demonstration of proof-of-concept. Such demonstrations are generally larger in scale and more resource intensive than exploratory research. Moreover, rather than exploratory, they are aimed at assessing the merit of a specific concept. Indeed, demonstration prototype efforts can be "resource sumps", as they are both uncertain and costly. Therefore, the DARPA Director has needs to attentively oversee these while maintaining and protecting the more exploratory research efforts.

DARPA's Successes

Over the fifty years since its inception DARPA has had several major accomplishments that distinguish it as an innovative organization.

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7 Licklider, J. C. R. (1960). "Man-Computer Symbiosis", *IRE Transactions on Human Factors in Electronics* 1: 4–11, https://doi.org/10.1109/thfe2.1960.4503259; Licklider, J. C. R., and Taylor, R. (1968). "The Computer as a Communications Device", *Science and Technology* 76: 21–31. See Waldrop, M. M. (2001). *The Dream Machine: J. C. R. Licklider and the Revolution that Made Computing Personal*. New York, NY: Viking Press.

Third Generation Info Tech—the Creation Interactive Information

The singularly most notable technology accomplishment that DARPA is known for is the development of what is now known as modern computing, as embodied in the personal computer and the Internet. While this achievement had its origins in the remarkable vision of one man, J. C. R. Licklider, its coming to fruition speaks volumes for the nature of DARPA as an organization and the willingness of its management to support and nurture the pursuit of such an extraordinary perspective.[8]

The vision that Licklider brought to DARPA was one of a totally revolutionary concept of computers and how they could be used. He foresaw that rather than being fundamentally highly automated calculating ma- chines, computers could be employed as tools in supporting humans in creative processes which he discussed in the article "Man-Computer Symbiosis" in March 1960's *IRE Transactions on Human Factors in Electronics*, volume HFE-1. However, to do so would require entirely new, yet non-existent computer capabilities that included interactive computers, internetted computing, virtual reality, and intelligent systems.

Licklider's extraordinary notion of "man-computer symbiosis" was a fundamental vision that foresaw using new types of computational capabilities to first achieve augmented human capabilities, and then possibly artificial intelligence. Licklider brought these inchoate notions to DARPA when he was named Director of its Information Processing Techniques Office (IPTO). He brought a powerful vision of what could be and used this as the basis for sustained investment in the underlying technologies to achieve the vision. This concept became the gestation of a concerted effort that culminated in the ARPANET, as well as a number of technological innovations in the underlying computer graphics, computer processing, and other capabilities that led to DARPA's fundamental impact on "making computers personal": a truly change-state vision which had fundamental impact in fostering a transformational concept and the creation of an entire industry.

8 Waldrop, M. M. (2001). *The Dream Machine: J. C. R. Licklider and the Revolution that Made Computing Personal*. New York, NY: Viking Press, provides considerable detail on DARPA's fundamental role in advancing computer technology.

DARPA's Role in Creating a Revolution in Military Affairs[9]

DARPA has been instrumental in developing a number of technologies, systems and concepts critical to what some have termed the Revolution in Military Affairs (RMA) that DOD implemented in the 1990s based on R&D conducted by DARPA over the prior fifteen years, according to the Institute for Defense Analyses paper *Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs*. It did so by serving as a virtual DOD corporate laboratory: a central research activity, reporting to the top of the organization, with the flexibility to move rapidly into new areas and explore opportunities that held the potential of "changing the business". DARPA acted as a catalyst for innovation by articulating thrust areas linked to overall DOD strategic needs, seeding and coordinating external research communities, and funding large-scale demonstrations of disruptive concepts. In doing so, the DARPA programs presented senior DOD leadership with opportunities to develop disruptive capabilities. When these programs received consistent senior leadership support, typically from the highest levels of the Office of the Secretary of Defense, they transitioned into acquisition and deployment. At other times, without this backing from the highest reaches of the department, only the less disruptive, less joint elements moved forward.

An example of one of the most successful DARPA programs is its championing of stealth. A radical and controversial concept, DARPA's stealth R&D harnessed industry ideas. Low-observable aircraft had been built before, for reconnaissance and intelligence purposes, but not pursued for combat applications. The Air Force had little interest in a slow, not very maneuverable plane that could only fly at night. After considerable engineering work, the Have Blue proof-of-concept system enabled top OSD and Service leadership to proceed with confidence to fund and support a full-scale acquisition program. OSD leadership kept the subsequent F-117A program focused on a limited set of high priority missions that existing aircraft could not perform well. For example, the program focused on overcoming Soviet integrated air defenses, and

9 This section draws upon Van Atta, et al. (2003). *Transformation and Transition*.

worked with Congress to protect its budget, with a target completion date within the same administration. The result was a "secret weapon" capability—exactly what DARPA and top DOD leadership had envisioned.

Sustaining the DARPA Vision

DARPA's higher-risk, longer-term R&D agenda distinguishes it from other sources of defense R&D funding. Perhaps the most important effect of DARPA's work is to change people's minds as to what is possible.

DARPA's fifty-year history reveals a constant mission to create novel, high-payoff capabilities by aggressively pushing the frontiers of knowledge—indeed demanding that the frontiers be pushed back in order to explore the prospects of new capabilities. As an entity DARPA has many of the same features as its research.

DARPA began as a bold experiment aimed at overcoming the usual incremental, tried and true processes of technology development. Like the research it is chartered to develop, DARPA has consistently been purposively "disruptive" and "transformational" over its fifty years.

Sustaining this unique ethos has not always been easy. There have been several efforts over the years to "tone DARPA down;" make its research more compatible and integrated into the rest of DOD R&D; have it focus more heavily on nearer term, more incremental applications—in other words make it behave like a normal R&D organization. There have been efforts to broaden its charter into system prototyping well beyond the proof-of-concept demonstrations it has constructed on several breakthrough systems. However, with strong internal leadership, both within DARPA and in the OSD, as well as support from Congress, DARPA has been able to perform a truly unique role—it has been and continues to be DOD's "Chief Innovation Agency", pushing the frontiers of what is possible for the benefit of national security and the nation as a whole.

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