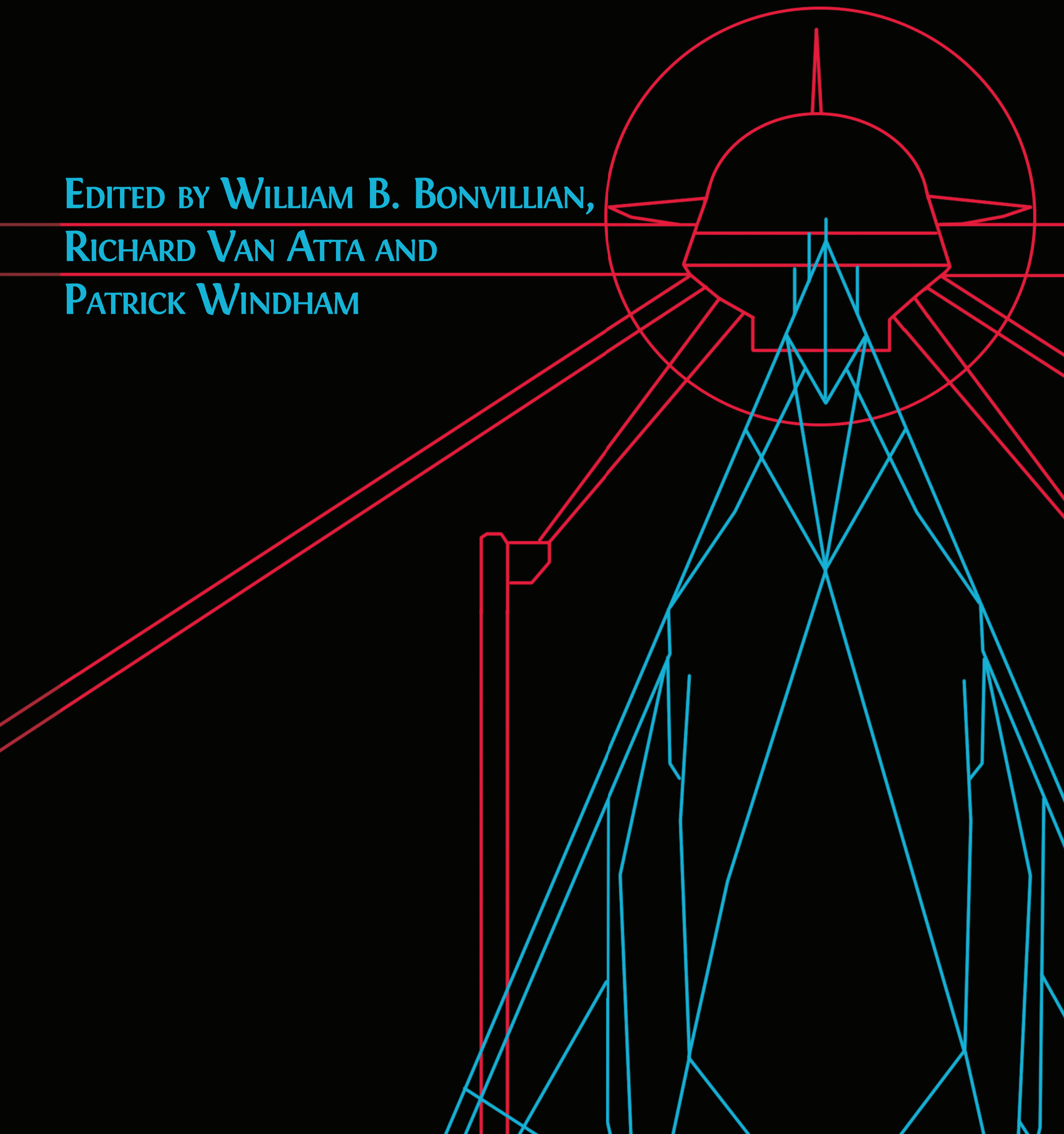
The DARPA Model for Transformative Technologies

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

Edited by William B. Bonvillian, Richard Van Atta and Patrick Windham



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8. DARPA's Process for Creating New Programs[1]

David W. Cheney and Richard Van Atta

Introduction

The U.S. Defense Advanced Research Projects Agency (DARPA) is widely recognized to be a highly successful R&D agency. It has been credited with making investments that have led to a large number of innovations and important advances in electronics, computing, and robotics, as well military advances such as stealth aircraft, smart weapons, and autonomous vehicles. In light of its success, there has been interest in learning from DARPA and adopting its methods. In the United States, there have been several attempts to apply the DARPA model to other agencies, including the Intelligence Advanced Research Projects Agency (IARPA), the Homeland Security Advanced Research Projects Agency (HSARPA), and the Advanced Research Projects Agency-Energy (ARPA-E). Other countries have also been interested in learning from the DARPA model. Most notably, in Japan, the Cabinet Office's Council on Science, Technology and Innovation has sponsored the ImPACT program, which was in part inspired by DARPA and is intended to support high impact, high risk R&D.

1 This paper was written for Japan's New Energy and Industrial Technology Development Organization (NEDO) and was completed in March 2016. The authors gratefully acknowledge NEDO's support.

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A key aspect of any successful R&D program is to pick the right problems to work on—problems that are both important and also addressable within the time and resources of the program. This typically is one of the greatest challenges in creating a successful R&D program. DARPA appears to be very successful at picking good problems to address, and it has a remarkable record of supporting timely and ground breaking projects. DARPA programs often appear to be unconventional and represent different choices than normal government or private R&D investment. How does DARPA identify and decide on these unconventional topics?

In recent years, literature on DARPA's management practices has emphasized:[2]

- DARPA's non-hierarchical and non-bureaucratic organization
- The role of highly talented, entrepreneurial program managers (PMs) who serve for limited (three- to five-year) duration
- That research is performed entirely under contract with outside organization
- The use of short-term funding for seed efforts to test promising concepts, and a clear willingness to terminate non-performing projects

With respect to the selection of focus areas, the literature has noted:

- DARPA's emphasis on ''high-risk/high-payoff'' projects, selected and evaluated based on the impact they could make to achieve a new capability or meeting a defense need.
- The key role that its program managers play in developing programs, gathering ideas from the technical community, making funding decisions and in managing programs, and working DARPA's technical community as well as the defense community.[3]

2 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, https://doi.org/10.1007/s10961-011-9223-x (Chapter 13 in this volume).

3 Fuchs, E. R. H. (2009). "The Road to a New Energy System: Cloning DARPA Successfully", *Issues in Science and Technology* 26/1, http://issues.org/26-1/fuchs/

Most studies have not focused specifically on where program ideas come from, and many studies have drawn their conclusions from one part of the agency, or at one time.

Against this research backdrop, NEDO Washington asked us to do a study of specific cases that illustrate how DARPA chooses its program areas. These cases focus on the selection of programs, not on the individual projects that make up programs (although the distinction is not always so clear, leading us to discuss a few major projects). Moreover, the focus is on the formation, and not the execution of programs.

We were asked to have the cases cover:

- Some well-known and easily understandable technologies
- A range of DARPA offices
- Programs that generated technologies for different military services
- A variety of time periods, with a preference for relatively recent projects.

Our study has several important limitations. First, the study was limited in scope, time, and resources, and is not comprehensive. While any R&D agency with more than fifty years of history cannot be fully characterized by a handful of case studies, a particular challenge in studying DARPA is that DARPA has changed over time and that its processes differ in different parts of the organization. DARPA is often recognized to be relatively free of bureaucracy, but the lack of rules and structure also leads to a lack of consistency throughout the organization and over time. As a result, while our study describes how DARPA has operated at different times and in different parts of the organization, it cannot be considered a complete description of how DARPA develops new programs.

Our selection of cases studies may also have several biases. Due to limitations in time and resources, we focused on programs for which information was more readily available. These included cases for which the authors personally knew key individuals who could discuss the cases, as well as cases that had already been well described, either by us or by others.

Most of our cases took place in the late 1980s and early 2000s, and many of our cases are concentrated in periods that are often considered somewhat atypical of DARPA. First, the period from 1988 to about 1996 was characterized by a very high interest in dual-use technology. The loss of industrial competitiveness in key industries and technologies, combined with changing defense needs with the end of the cold war, led to an expansion of programs that were outside of DARPA's traditional mission and were intended to help support the competitiveness of key industries. During this period, Congressional and Administration priorities exerted an unusual influence in creating new programs.

Second, the period from 2001 through 2008 was characterized by unusually strong top-down direction, due to the management style of the director during this period, Dr. Anthony (Tony) Tether. Programs that were started in this period tended to have more influence from the DARPA director than in most other periods. Thus, while there is no single period of DARPA's history than can be described as completely typical, the period in which many of our cases are concentrated are notably atypical.

There are several other sources of potential bias in the selection of cases. One is that it is easier to get information about programs that DARPA chooses to publicize. Like most organizations, DARPA highlights its successes more than its failures. When DARPA makes information available on a program, program managers are less inhibited in discussing it, and journalists or analysts are more likely to write about it, all of which increases the information on the program available in the public domain. DARPA programs that are well-known may differ systematically from less visible programs.

Because we did not do a random sample of DARPA programs, we cannot generalize our findings to all of DARPA. Other analysts, looking at different parts of DARPA at different times, may come to different conclusions. Several of our interviewees reported that they viewed their program as an atypical DARPA program. Indeed, one of the findings of the report is that atypical programs are common.

A further limitation is that each case is not comprehensive. In most cases we relied on one interview supported by background materials; it is quite possible that other participants would have different perspectives on each case.

General Framework and Typical Patterns of Program Development

Figure 8-1 illustrates the influences on the development of new programs at DARPA. As will be discussed in the case descriptions, not all of the influences are present in every case, and the relative strength of the influences from the various sources differs significantly among the cases.

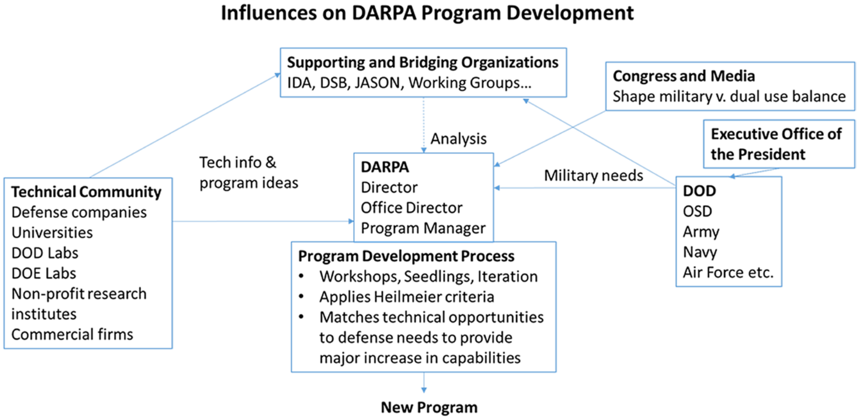

Fig. 8-1 Influences on DARPA's Program Development. Source: TPI. Notes: IDA is Institute for Defense Analyses; DSB is Defense Science Board; JASON is a group of high-level government science and technology advisors; DOD is Department of Defense; DOE is Department of Energy; OSD is Office of the Secretary of Defense. (Figure prepared by the authors.)

In the archetypal DARPA program development process, information concerning useful new capabilities comes from the Department of Defense, while information concerning what is technically possible, and what areas might be ripe for advancement, comes from the technical community. Information and analysis may come from the community of think tanks and advisory committees that advise the Department of Defense and DARPA. The DARPA program manager has the responsibility for taking this input and constructing a program, usually made up of a set of projects, with defined technical goals that are aggressive but can potentially be met within a defined time frame and within a budget. The PM (Project Manager) must put together a program that is sufficiently challenging, important, and doable, to be approved by the office director and ultimately the DARPA director. The "Heilmeier Catechism" (see Table 8-1) provides a set of questions the DARPA program managers should be able to answer to get approval for their program.

Table 8-1 Heilmeier's Catechism.
Source: https://www.darpa.mil/work-with-us/heilmeier-catechism

George H. Heilmeier (DARPA director 1975-1977) developed a set of questions known as the "Heilmeier Catechism" to help Agency officials think through and evaluate proposed research 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 is new in your approach and why do you think it will be successful?
- Who cares? If you succeed, what difference will it make?
- What are the risks?
- How much will it cost?
- How long will it take?
- What are the mid-term and final "exams" to check for success?

Within the broad categories of groups that provide information into the program development process, there are many subcategories. Within the Department of Defense, there may be input from the military services (Army, Navy, and Air Force) as well as the Office of the Secretary of Defense (OSD), and these may all have different views on the importance of new technology. Within the technical community, there are universities, defense laboratories, defense contractors, and others, each of which bring different viewpoints. Of special influence are the parts of technical community that have had long-term interactions with DARPA, as contractors and as sources of program managers.

There are many variations in the influences on programs. In some cases, the military need drives the process, and the program is set up to develop a prototype that may not require fundamental advances in technology. In other cases, the DARPA director or a DARPA office director may drive the process. They may have particular interests that they believe DARPA should pursue, and they will recruit a program manager to execute a program built around those interests. In other cases, the drive may come from DARPA's technical community, which may make DARPA aware of the potential that advances in science and technology may have for the military. In some cases, a general need may come from the defense community, but the key ideas that form the basis for a program may come from the technical community, in workshops or in response to a Request for Information (RFI) or a Broad Agency Announcement (BAA). In some cases, outside advisors, the Congress, and/or the Executive Office of the President (including the President's key science, economic, and national security advisors) have played important roles in shaping DARPA programs.

The different DARPA offices can vary in their processes for program development. In general, the Defense Sciences Office (DSO) can be expected to interact more with the research community while the Strategic Technology Office (STO) and Tactical Technology Office (TTO) tend to interact more with the military services. The other three technical offices—the Biological Technologies Office (BTO), Microsystem Technology Office (MTO) and Information Innovation Office (I2O)—are somewhere in between.

The influences on DARPA program development have also changed over time. In DARPA's early days, much of its work was driven by large defense projects in space, missile and satellite development (especially before NASA was established) and nuclear test detection. In the late 1960s and early 1970s, the needs of the Vietnam War were a major influence. In the late 1970s into the mid-1980s, DARPA initiated major thrusts in radically new weapons concepts, such as stealth aviation and standoff precision strike. In the late 1980s and early 1990s, DARPA was given new dual-use roles by the Congress and the Administration, and funds for industrial consortia in semiconductors, optoelectronics and other areas were administered by DARPA. In much of the 2000s there was a refocusing on defense applications, as well a strong top-down influence from the Director, Anthony Tether.

These various influences on DARPA program development are illustrated in the next section through case studies.

Case Studies of the Development of DARPA Programs

We focused our study on the nine cases of the development of DARPA programs as described in Table 8-2.

Table 8-2 Case studies in this chapter. (Table prepared by the authors.)

Case[3]	Period	DARPA Office	Idea Origin
Have Blue (Stealth)	1974-1981	TTO	OSD
Assault Breaker	1978-1984	TTO	External DARPA-funded studies
Amber (High Altitude, Long Endurance Unmanned Aerial Vehicles)	1978-1986	TTO	OSD
Optoelectronics (Wavelength Division Multiplexing)	1989-1992	DSO and MTO	PM and community
High Definition Systems	1989-1993	DMO	DARPA Director
Magnetic Materials / Spintronics	1993-2005	DSO	PM
Personalized Assistant that Learns (PAL) led to SIRI)	2002-2009	IPTO	DARPA director and IPTO Office Director
Topological Data Analysis	2004-2008	DSO	PM
Revolutionizing Prosthetics	2005 to present	DSO to BTO	Need driven

In each case, we have tried to focus on a specific program, but we discuss related activities that preceded and followed the program. In some cases, the identification of a program for analysis, and when it started, is not so clear, as the agency may have funded small projects before the main program began, so the precursors to a program may have begun well before the DARPA program was created.

For each program, we characterize the program by name, goal, DARPA office, time period, and main results. Then we examine the history of the program and where the idea for the program came from. Whose idea was it? How advanced was the idea when DARPA took it on? Were there antecedent ideas and programs? Was the program part of a broader and long-standing set of DARPA activities? How long was the proposal in development? Were there small projects, termed "seedlings", to test key concepts before the main program was established? Was the program significantly modified in goals or approach?

We discuss the background of the program managers and their role. What were they hired to do? Did the PMs have the idea, were they given the idea, or did they find the idea? Then we discuss other key roles in the formation of the programs including the role of the technical community, the DARPA senior management, and other elements of the Department of Defense.

Finally, we discuss the lessons learned from the case and what the case illustrates about DARPA's process of program formation.

Have Blue (Stealth)[4]

Overview

The "Have Blue" program was the DARPA program that produced the original prototype "stealth" aircraft that is much less visible to radar and other detection methods. It was managed in the Tactical Technology Office.

Planning studies began in 1974, and the program to develop the prototype plane took place in 1976 to 1978, with subsequent follow-on support to the Air Force through 1981. The program was highly successful, and led to a new generation of aircraft, starting with the F-117A, that represented a major increase in military capabilities.

4 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, 11–15, https://doi.org/10.21236/ada422835, https://fas.org/irp/agency/dod/idarma.pdf

Context and history of the program development

Origins

By the early 1970s it was clear to the U.S.'s strategic defense planners that the Soviet Union had achieved air defense capabilities that would have made penetrating Soviet airspace difficult. This presented the U.S. with a fundamental strategic challenge, requiring the development of new alternatives if the U.S. and NATO were to deter or combat the Soviet Bloc without having to resort to nuclear war. A central party to address this threat was the Director of Defense Research and Engineering (DDR&E) of the Office of the Secretary of Defense, who at that time was Dr. Malcolm Currie. Currie assumed this position in 1974 and, based on guidance from Secretary of Defense Schlesinger, sought greater innovation from the defense research community to develop emerging technologies to address the Soviet military buildup.

It was in this larger context in 1974 that Chuck Myers, Director of Air Warfare Programs in the Office of the DDR&E, mentioned to Robert Moore, then Deputy Director of DARPA's Tactical Technology Office (TTO),[5] an idea he called the "Harvey concept".[6] The concept was to create a tactical combat aircraft that was much less detectable by radar or infrared, acoustic, or visual means.

A primary objective was to use only passive measures (coatings and shaping) rather than depending on support aircraft carrying jammers. Such a plane would allow for new types of deep air attacks, replacing the "air armada" tactics using a large number of aircraft that had become the norm in Air Force and Navy aviation.

The Harvey idea was not entirely new, as some techniques to make aircraft less visible had been used in highly classified reconnaissance aircraft (both manned and unmanned). However, there were no serious efforts to employ such capabilities on a weapons platform. To do this, significant advances in radar cross-section reduction were needed to overcome Soviet integrated anti-aircraft systems. Myers wanted to fund aircraft companies to propose conceptual designs. Coincidentally, shortly after the Myers-Moore discussion, DDR&E Malcolm Currie sent

5 Moore became TTO Director in 1975.

6 "Harvey" was the name of an invisible rabbit in a popular play and 1950 movie of the same name.

out a memo stating that he was not satisfied with the innovation he saw coming out of DOD research. The memo also invited organizations to propose radical new ideas. Representing the TTO Office, Moore nominated the "Harvey" idea, renaming it "High Stealth Aircraft".

Ken Perko from the Air Force Systems Command at Wright Patterson Air Force Base had recently been recruited as a program manager to build up a tactical air program within DARPA's TTO. Perko had worked in the Air Force on DARPA-sponsored work on "low-observable" research for drones and remotely-piloted vehicles, and had some knowledge of this field. DARPA's Moore therefore assigned Perko the task of contacting U.S. defense aviation contractors directly to solicit their ideas on approaches to achieve extremely low radar cross-section. Moore recalled that most of the vendors submitted slightly improved radar cross-section reduction, but nothing that would reach the order-of-magnitude goals that DARPA was seeking. Based on these initial submissions, DARPA ultimately funded small preliminary studies at Grumman, McDonnell-Douglas, and Northrop. Three formal study contracts followed, awarded to McDonnell-Douglas, Northrop, and Hughes (for its radar expertise). While these studies were under way, Lockheed became aware of the project (Lockheed had not been invited to participate initially because it was not considered to be active in tactical aircraft) and contacted DARPA requesting permission to participate in the first phase concept development, without compensation. This request went to DARPA Director George Heilmeier, who granted Lockheed permission.

DARPA Have Blue Prototype

By the summer of 1975, it was clear that only Lockheed and Northrop had credible, near-term concepts for making aircraft radically less visible to enemy antiaircraft radar. Perko, Moore and Heilmeier met to develop a strategy and decided that a full-scale flight demonstration would be needed to make the results convincing. However, Heilmeier insisted that the program should not go forward without Air Force backing. Air Force support was highly uncertain, as the Air Force saw limited value in a stealthy strike aircraft, given the severe performance compromises that they assumed would be required to achieve a very low radar cross-section. There were also competing Air Force R&D priorities, most notably the Advanced Combat Fighter program (which eventually became the F-16).

DDR&E Currie discussed the problem directly with General David Jones, the Air Force Chief of Staff, and General Alton Slay, the Air Force R&D Director. Although the Air Force remained skeptical as to a stealth strike fighter's value, Currie and Jones brokered a deal to obtain active Air Force support for the DARPA stealth program, provided that funding for the stealth development would not come out of existing Air Force programs, especially the F-16. With that agreement, Phase II of DARPA's stealth aircraft program—Have Blue—began in 1976. Lockheed won the sole Phase II award, in part due to the record of its "Skunk Works"[7] for on-schedule accomplishment of high-risk, high-classification projects, especially the SR-71 Blackbird.

Have Blue was a quarter-scale proof-of-concept aircraft designed to evaluate Lockheed's concept for "very low-observable" capabilities while meeting a set of realistic operational requirements. The development program at Lockheed's Skunk Works was highly classified (a Special Access Program or SAP), but managed in an environment open to experimentation and flexible problem solving, with a high degree of communication among scientists, developers, managers, and users. Shortly after the program began, its management was transferred to the Air Force, due to its being highly classified. Importantly, only a total of a dozen or so people in OSD, DARPA and the Air Force knew of the Have Blue program. OSD leadership under Currie and Myers kept the program focused and moving forward in the face of many fundamental uncertainties.

Transition to Air Force—Senior Trend

Successful flights of Have Blue planes in 1977 made it clear that a stealthy aircraft could be built and flown. Based on these results—and guided by the high priority of countering Soviet numerical superiority with U.S. technology—Currie's replacement in the Carter

7 "Skunk Works" was the name given to Lockheed's Advanced Development Programs (ADP), which was famous for rapidly developing new airplanes in an un-bureaucratic environment, https://en.wikipedia.org/wiki/Skunk_Works.

administration that took office in January 1977, Under Secretary of Defense (Research and Engineering) (USD(R&E)) William Perry sought accelerated development of a real weapons system. The DARPA stealth program was then immediately transitioned to an Air Force acquisition program—called "Senior Trend"— with an aggressive schedule to have operational planes in only four years, forgoing the normal development and prototyping stage. The objective was to build and deploy a wing of stealth tactical fighter-bombers (seventy-five planes) as rapidly as possible. Furthermore, in order to obtain the largest possible technical lead, it was deemed necessary to hide the acquisition by making Senior Trend a highly secret program. The resulting operational aircraft was dubbed the F-117A.

Impact

The first F-117A "stealth fighter" was delivered in 1981, and fifty-nine were deployed by 1990. In 1991, the F-117A was an outstanding success in the Gulf War. It helped the U.S. achieve early air superiority critical for defeating heavily defended targets. It did so in the face of the same type of Soviet anti-aircraft systems that had been effective against U.S. aircraft in Vietnam and other wars. In championing stealth, DARPA harnessed ideas from industry and the military service laboratories to pursue a radical new warfighting capability. Stealth combat systems had not been pursued because the Services lacked a strong interest in such a nontraditional concept. With high-level support from civilian leadership across presidential administrations, DARPA overcame that resistance, set out priorities, and obtained funding for the considerable engineering work to develop a proof-of-concept aircraft demonstration system. This demonstration enabled top civilian and Service leadership to proceed with confidence. OSD and Service leadership, once persuaded, rose to the challenge, and provided funding and support to implement a full-scale weapons program.

From the outset Have Blue was a "crash" program, designed to develop and deploy a breakthrough capability in as short a time as possible. Achieving this required a highly focused technology development, prototyping and acquisition approach. The approach was driven by a national-level strategic imperative that was initiated out of the Office of the Secretary of Defense and developed by DARPA. The subsequent implementation was through a highly classified Air Force Program with direct and close oversight of the Under Secretary of Defense for Research and Engineering. Throughout this process the focus was delivering an operationally capable stealth strike aircraft in four years. The imperative of offsetting the Soviet air defense capabilities drove decisions on the structure of the program, the selection of the performer, the oversight mechanisms. The program had ambitious but clear objectives that helped focus the contractor and the government on working together pragmatically to achieve the outcome.

Background and Role of the Program Manager

Ken Perko, the program manager for Have Blue, worked closely with TTO Director Robert Moore in (1) getting industry inputs, (2) assessing the competing approaches, and (3) selecting the eventual contractor, Lockheed, to produce the Have Blue prototype. While Perko had earlier experience in related DARPA programs in low observables when working for the Air Force, the idea to actively pursue such a radically different aircraft came from the top down, led by Myers and supported at DARPA by Moore.

Other Key Roles in Program Formation

Myers (Director of Air Warfare Programs in the Office of the DDR&E) was the true instigator of a "stealthy" tactical aircraft—initially called "Project Harvey". Indeed, Myers was a driver of new aviation concepts more broadly, including the notion of a mini-fighter that would be intrinsically low-observable. In essence he was OSD's aviation leader and engaged the Services and DARPA actively to pursue new ideas.

DARPA Director George Heilmeier was both a champion and a skeptic. He was an advocate of pursuing radical new concepts, and especially in scaling these up as proof-of-concept demonstrations. However, he also realized that only the Air Force could actually produce a successful aircraft weapon system. Therefore, he insisted that Air Force backing be obtained, which required intervention by Dr. Currie, the DDR&E. Heilmeier was actively involved with Moore and Perko in strategizing how the program should be scoped and conducted. His involvement was predicated on Have Blue being such a high-priority program with such high-level interest (as well as being a very high-cost program relative to most DARPA programs).

Director of Defense Research and Engineering (DDR&E) Currie had sent out a memo stating that he was not satisfied with innovation he saw coming out of DOD research. The memo also invited organizations to propose radical new ideas. Representing the TTO Office, Moore nominated the "Harvey" idea, renaming it "High Stealth Aircraft". Currie subsequently used his office to leverage Air Force participation in Have Blue and subsequently the Senior Trend program that led to the F-117A.

Moore focused DARPA's involvement in the Have Blue program. He took on Myers' challenge to see whether an "invisible" combat aircraft was possible and worked with program manager Perko to determine the options and develop the approach.

Key Insights

Have Blue shows that DARPA could be extremely responsive to high-level priorities of OSD and indeed the White House. DARPA saw itself as the organization that could and should take on high-risk programs that could fundamentally improve the national security position of the United States. This was exactly what it did in response to DDR&E Currie's (and Defense Secretary Schlesinger's) call for greater defense innovation to meet the Soviet threat. OSD articulated the challenge—can a stealthy aircraft be made? DARPA organized and funded the research to discern what could be done and then developed the prototype that demonstrated this.

DARPA conducted Have Blue as a "black program"—classified above Top Secret. This was done to keep the Soviet Union from knowing what was being done. Importantly, such programs are known within the DOD to very few, and also very few individuals outside (including only a handful in Congress). This permits them to proceed with less scrutiny than is the norm. However, such classification places a great deal of extra burden on the project management.

Have Blue shows the role of civilian leadership in pushing concepts that the military services resist. Stealth combat systems had not been pursued by the Air Force because they conflicted with their priorities and concepts for combat aviation. The Air Force lacked interest in such a nontraditional concept that compromised performance—especially speed, maneuverability, and self-defense. However, with high-level support from civilian leadership across administrations, DARPA overcame that resistance, set out priorities, and obtained funding for the considerable engineering work to develop a proof-of-concept aircraft demonstration system. Have Blue is also an example of where an OSD-identified need led DARPA to fund several conceptual studies, and then DARPA developed the most promising of these into a program. Such conceptual studies can be a key part of program development.

Assault Breaker (Standoff Precision Strike)

Overview

Assault Breaker was the demonstration of a concept for finding, hitting and destroying targets on a battlefield from a distance—known as "standoff precision strike"—by employing a "system of systems". The program combined airborne radar, long-range tactical ground-based missiles and terminally-guided submunitions, linked to a rapid, all-source targeting system. The Assault Breaker program began in 1978 and concluded in 1983, and was run through DARPA's Tactical Technology Office (TTO). It is generally recognized that the result of this program was a joint operational concept that would revolutionize the battlefield.[8]

Context and History of Program Development

Assault Breaker had its origins in a DARPA study jointly funded with the Defense Nuclear Agency (DNA) to define alternatives to allow the United States "to respond flexibly to a military threat from an aggressor nation". This was a large, multi-participant study comprised of strategic thinkers and technologists who were drawn together as the "New Alternatives Panels", organized under DARPA and DNA to respond to Presidential, National Security Advisor, and Secretary of Defense concerns that there was a need to "broaden

8 Van Atta, et al. (2003). *Transformation and Transition. Volume 1*, 15–16.

the spectrum of strategic alternatives" available (other than nuclear strike) to "limit Soviet aggression".[9] The classified work of these panels was simply titled the *Long Range Research and Development Plan*. These deliberations converged around new defense concepts that emphasized standoff precision strike. It was understood that to actually combine capabilities to do this would require unproven and unprecedented integration of a wide variety of technologies that dictated a unified development, integration and employment of both targeting and weapons systems.[10]

DARPA was given the task of implementing the precision strike concept based on the integration of inputs from (1) the Long-Range Research and Development Planning Program; (2) ideas from DARPA program manager Leland Strom for using Moving Target Indicator (MTI) radar to guide a missile to a target area and then use terminally guided submunitions to destroy the targets; and (3) briefings from industry on using tactical missiles with submunitions with electro-optical seekers. The Director of DARPA's Tactical Technology Office, Moore, drew upon these ideas to propose the Integrated Target Acquisition and Strike System (ITASS) as a DARPA program to develop and demonstrate such capabilities. Moore asked MIT's Lincoln Laboratory to flesh out this concept, including potential systems that could be incorporated, and the feasibility of enabling technologies that would be needed.[11] When DARPA Director Robert Fossum approved the program in 1978 it was renamed Assault Breaker.

Establishing the Assault Breaker Program

There had been several rather disparate R&D efforts of the military services on parts of the technology underpinnings of what became Assault Breaker, such as the newly deployed E-3 Sentry (AWACS) aircraft, which led to the DARPA-Air Force Tactical Air Weapons Direction System Program (TAWDS), which then was renamed Pave Mover.

9 *Ibid*., 16, quoting *ARPA/DNA* Long Range Research and Development Plan, *Final Report of the Advanced Technology Panel* (1975), vi.

10 Van Atta, et al. (2003). *Transformation and Transition*. *Volume 1*, 8.

11 *Ibid*., 18.

Pave Mover was then merged into the Assault Breaker program, and subsequently became JSTARS (Joint Surveillance Target Attack Radar System).[12] Similarly the Air Force and Army were both working on various programs to develop new munitions for attacking ground targets and ways to deliver these from a distance including an array of submunitions that could be directed to individual targets, including the Air Force's Wide Area Anti-Armor Munitions (WAAM) and the Army's Terminally Guided Sub-Munition (TGSM). These new individual weapons technology concepts were all inputs to Moore in DARPA's Tactical Technology Office, and all influenced DARPA PM Leland Strom in formulating a concept that integrated such capabilities, which he presented to Moore. These separate developments in sensing, missiles, submunitions, as well as command and control, were inputs into an *integrated* capability (system of systems) in a DARPA-funded project (ITASS) conducted by Lincoln Laboratory.

While these concepts were developed by 1976, the actual Assault Breaker Program to develop and demonstrate these integrated capabilities did not start until 1978. This was the result of several factors: (1) the change of Administrations in 1976, bringing in new leadership; and (2) concerns by new DARPA Director Fossum that the Assault Breaker was "fragile" in combining multiple capabilities that were unproven both individually and together in a combat environment. Moreover, Assault Breaker was itself different from "normal" DARPA military programs in that it was more about integration of several relatively near-term technologies, rather than a leap in technology itself. Thus, DARPA Director Fossum and his immediate superior, Under Secretary of Defense for Research and Engineering (USDR&E), William Perry, both new to the Pentagon in 1976, had to evaluate the complex proposals for standoff precision strike and determine whether and how to proceed. It should be noted that both Fossum and Perry were well versed in the earlier developments through their industry backgrounds and as advisors to DOD. Moreover, Perry was an enthusiastic advocate for the overall concept of standoff precision-guided weapons, as articulated in his testimony in 1978 upon becoming USDR&E.

12 Van Atta, R., Deitchman, S., and Reed, S. (1991). *DARPA Technical Accomplishments. Volume II*. Alexandria, VA: Institute for Defense Analyses, 5–6, https://apps.dtic.mil/dtic/tr/fulltext/u2/a241725.pdf

Background and Role of the Program Manager

The Assault Breaker program was the result of higher-level inputs above the DARPA program manager. The key individual in developing the program was Moore, who was Director of the Tactical Technology office. Assault Breaker was driven by a high-level strategic imperative from the White House (President Nixon and Security Advisor Kissinger) to address Soviet military capabilities threatening Western Europe. This translated into a DARPA-DNA sponsored study group that identified the general concept of standoff precision strike using conventional weapons as a way to "offset" Soviet-Warsaw Pact armor. However, it was Moore who harnessed inputs from a TTO program manager, Leland Strom, and inputs from industry, into an initial study by Lincoln Laboratory and then used that to formulate the Assault Breaker Program.

Other Key Roles in Program Formation

Assault Breaker was in fact a multi-project four-phase program, with these sub-projects managed by a set of DARPA TTO PMs. For example, the Pave Mover airborne reconnaissance aircraft (which subsequently became JSTARS) was under PM Nicholas Willis. In its first phase, the program supported continued development of individual component technologies, such as the sensors, radars, and automatic target recognition—most of which were being pursued within DARPA under various PMs. The second phase was then testing in parallel different contractor approaches for systems level capabilities. In the third phase, more complex integration of systems-of-systems was demonstrated in competition. Finally, the fourth phase linked together the integrated system into a large, complex demonstration.[13]

Assault Breaker was managed under a unique approach under DARPA with an actively involved steering group that included the Director of DARPA, Fossum, as well as Lt. Generals from both the Army and the Air Force. Notably DARPA reported directly to Under Secretary of Defense (Research and Engineering), Perry for this project. Moreover, Moore was elevated from DARPA to the position of Deputy

13 These phases are described in specifics in Van Atta, et al. (1991). *DARPA Technical Accomplishments*. *Volume II*, V-9, V-10.

Under Secretary of Defense for Tactical Warfare Programs, to provide continued oversight of this and related programs.[14] DARPA was thus given direct responsibility for managing what became a combined set of projects conducted mainly under the Army and Air Force.

Key Insights

The Assault Breaker program is an example of a very large-scale systems integration project, driven by highest-level military priorities, with the DARPA office director playing a key role in orchestrating the development of the implementing concepts.

- DARPA first supported a conceptual study (with the DNA) to determine an overall concept to meet a high-level security problem.
- DARPA then funded under the Office Director's initiative a detailed technical assessment of options and approaches for the integrated system-of-systems.
- Assault Breaker was an integration of multiple projects that were being individually pursued and managed by a set of DARPA PMs mostly being supported by individual military services. DARPA fostered the demonstration of these as an integrated system, which was largely counter to the culture and priorities of the separate military services.
- A unique management structure reporting to the Under Secretary of Defense (Research and Engineering) was established with the DARPA Tactical Technologies Office conducting day-to-day management.
- Program managers played primarily a management oversight role over very large individual sub-programs and their overall integration into a proof-of-concept demonstration.

14 Assault Breaker was in fact one of several large-scale DARPA programs for developing an integrated response to the Soviet Bloc. Another one was the Stealth aircraft program reported upon here as well. Moore moved to his position in OSD to provide broad oversight of all these programs as they matured and transitioned.

Amber/Predator (High Altitude Long Endurance UAVs)

Overview[15]

Amber, out of which grew the Predator unmanned aerial vehicle (UAV), was a specific program that developed from the Teal Rain program for advancing technologies for High Altitude Long Endurance (HALE) UAVs. The UAV that became Amber was proposed to DARPA in 1978 by its developer, Abraham Karem, who owned a firm called Leading Systems, Inc. The PM whom he briefed did not pursue the idea, but DARPA Director Fossum heard the presentation, overruled this rejection, and funded it out of his own office's funds. Based upon this support, Karem successfully developed and demonstrated a UAV called Albatross. DARPA then in 1984 began a program for Amber, a scaled-up version of Albatross. Amber was a classified reconnaissance UAV, which was flown in 1986—just two years after the initial DARPA contract. However, Amber was used only in small numbers (by the CIA), and, with no subsequent DOD business, Karem's firm, Leading Systems, Inc., went into bankruptcy and was sold to General Atomics. After a decade of delay, OSD pushed renewed interest in HALE UAVs and Amber was modified under a DARPA program to become Predator, an extremely successful intelligence, surveillance and reconnaissance (ISR) system that has been used extensively by U.S. and allied forces in conflicts in Iraq and Afghanistan.[16]

Context and History of the Program Development

The concept of an unmanned aerial vehicle can be traced as far back as World War I with a British radio-controlled "guided explosive laden unmanned air vehicle [intended] to glide into German ships". During World War II Germany further developed radio-controlled rockets,

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15 Van Atta, R. H., Cook, A., et al. (2003). *Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs.* Volume 2. Washington, DC: U.S. Government Printing Office, VI-2, VI-5, https://doi.org/10.21236/ada422835, https://apps.dtic.mil/dtic/tr/fulltext/u2/a422835.pdf

16 Predator was subsequently fitted with a missile that allowed it to become an attack weapon itself.

including the V-1. During World War II the United States converted B-17s into BQ-7 radio controlled "flying bombs", and then after the war modified additional B-17s as the QB-17G for such purposes as collecting atmospheric samples from nuclear tests, and later as target drones. The Air Force in the 1960s worked with Ryan Aerospace to develop an unmanned reconnaissance aircraft called the Firebee, which was used to conduct reconnaissance over North Vietnam and southern China, particularly to substitute for the manned U-2 spy plane in heavily defended areas. The Firebees were air-launched from a C-130 aircraft. With the termination of the Vietnam conflict, and subsequent drawdown of forces, Air Force interest in UAVs waned.

DARPA and UAVs

DARPA's initial involvement with UAVs was with remotely piloted vehicles (RPVs) used first in support of tactical reconnaissance in Vietnam.[17] However, by the early 1970s the expense and complexity of these earlier systems led to their demise, and the Director of Defense Research and Engineering, John Foster, urged that DARPA should focus instead on using lightweight, rugged, inexpensive model airplane technology, which became DARPA's Mini-RPV program. That program led to the successful development and testing of relatively small, fixed-wing UAVs, but these did not transition into any operational UAVs, as the Army's Aquila program which was based on these ultimately failed when requirements, weight and costs spiraled out of control. Thus, DARPA's first foray into UAVs ended with little actual deployed capabilities.[18]

DARPA High Altitude Long Endurance UAVs

In 1978, DARPA funded the aircraft developer Abraham Karem to develop a very-long endurance very high altitude (90,000 feet and 5-day

17 Van Atta, et al. (1990). *DARPA Technical Accomplishments*. *Volume I*, 28–23, 28–25.

18 It should be noted that the technologies did become further developed and deployed as combat systems by Israel as the Mastiff, Scout and Pioneer UAVs. Ironically, the U.S. Navy and Army acquired the Pioneer from Israel and eventually this led to the development of the Shadow tactical UAV by AAI, which is now part of Textron. See Hirschberg, M. J. (2010). "To Boldly Go Where No Unmanned Aircraft Has Gone Before: A Half-Century of DARPA's Contributions to Unmanned Aircraft", *American Institute of Aeronautics and Astronautics* (January): 11–13.

flight endurance) UAV under the Teal Rain program. Teal Rain was a classified DARPA program to explore technology for long endurance UAVs driven by the problem that prior efforts, largely by the Air Force, had resulted in very large and expensive aircraft. Teal Rain projects were expressly "unfettered, technology-push studies to generate new ideas".[19] Based on this initial support Karem, using his own funds, and under his own firm, Leading Systems, Inc., built prototypes of a new UAV, the Albatross, for which DARPA then supported flight tests. DARPA then began a program in 1984 for Amber, a scaled-up version of Albatross. Amber was a classified reconnaissance UAV, which was flown in 1986—just two years after the initial DARPA contract.

From a technical standpoint Amber was highly successful and Leading Systems invested in considerable technology development for improving performance and operational capabilities. However, in 1987, when the program was transferred to the Navy, Amber became a victim of Navy funding priorities. Moreover, Congress established within the DOD a Joint Program Office for UAVs consolidating all the military efforts.

With existing UAVs meeting then current Service requirements, the more advanced Amber was not selected to continue into acquisition. Leading Systems could not survive this misfortune and was sold first to Hughes and then to General Atomics. Karem, now associated with General Atomics, kept the Amber concept alive by developing a lower performance version called the Gnat 750, which was aimed at the international market. A few were sold to Turkey. Others were acquired by the CIA, which supported further development.

Predator

In 1990 the Joint Requirements Oversight Council (JROC) of the Joint Chiefs of Staff established a requirement for Long Range Endurance Reconnaissance, Surveillance, and Target Acquisition. The JROC put forward a three-tier approach for this.[20] Tier I was a quick reaction

19 Van Atta, et al. (2003). *Transformation and Transition*. *Volume 1*, VI-15, quoting DARPA Program Manager Charles Heber.

20 The three-tier concept was articulated in a memo by Deputy Secretary of Defense John Deutch. Tier III was to be a very high altitude, long endurance stealthy UAV. After considerable machinations, Tier III devolved into two alternative

capability that could be satisfied by the General Atomics Gnat 750. Tier II was labeled "Medium Altitude Endurance" and a scaled-up version of the Gnat 750 was seen as the best approach for this. This became the Predator. Predator was initially an incremental modification of the Gnat 750—essentially a stretched airframe and longer wings with additional ISR sensors—with linkage to satellite system for communications. Subsequent developments added substantial new operational capabilities for target acquisition and strike. The initial system comprised an aircraft, sensors, communications capabilities, and a ground station for aircraft control. Subsequently, laser target designator capabilities and then Hellfire missile launch capabilities were added.

As an aircraft, Predator is not highly complex. Primary complexities were involved in the control software and in the satellite communications linkage. The operational linkage through the Ground Control Station was a complicating factor. The technologies were generally mature. Most of the technology had been developed under DARPA, although with limitations and iterative developments. A major new development was use of satellite communications. Predator used GPS satellites for navigation, being the first UAV to overcome line-of-sight range limitations through use of satellite technology. Predator used commercial satellite data links for control and imagery transmission.

While much of the technology in the Predator system was in place, the implementation of a tactical intelligence, surveillance, and reconnaissance (ISR) UAV in the field was largely untried. The implementation of this system became an urgent priority of Office of the Secretary of Defense (OSD)-driven due to a need to have ISR capabilities to support efforts in Bosnia and later in Iraq. Consequently, Predator was developed as an urgent program, although not based on formal military-service derived requirements. The Gulf War in 1991 highlighted serious deficiencies in airborne tactical-level ISR, particularly for wide-area coverage. The Predator arose out of high-level (Secretary of Defense, Under Secretary of Defense, Joint Chiefs of Staff, Director CIA) concerns that these ISR capabilities needed to be kept affordable.

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platforms—Tier II+, which became the Global Hawk UAV, and Tier III-, which was called Dark Star, a smaller, stealthy system. Dark Star was cancelled after two crashes and costs that escalated excessively. Global Hawk subsequently became very successful in operations in Iraq, Afghanistan and elsewhere.

Predator was put into service using a "non-standard" accelerated process known as the Advanced Concept Technology Demonstration (ACTD) process. Use of the ACTD "allowed use of a streamlined management and oversight process, provided for early participation of the user community, and bound the schedule length. The goal of the ACTD was to demonstrate military utility in a relatively short timeframe. The use of mature technology was intended to limit risk".[21] Under the ACTD process, Predator was delivered for user experimentation in just six months. Predator was successfully employed in Bosnia (just a year after its first flight), Kosovo, and the no-fly zone in Iraq. Predator was later used in Afghanistan, becoming a weapons platform, firing Hellfire missiles.

Predator provides a clear example of a successful demonstration of innovative new capabilities prior to their being identified as military requirements. With this demonstration the operational community championed the novel HALE UAV capabilities for use in combat. Through this demonstration "technology push" became "demand pull" and the Predator went from demonstration to an accelerated acquisition. Of paramount importance was the fact that Predator met a compelling need for which there was no existing system, and that it was able to evolve to meet additional needs as these were identified.

Background and Role of the Program Manager

The program manager for the HALE Program was Charles Heber who served as director of the High Altitude Endurance Unmanned Air Vehicle Joint Program Office at the Defense Advanced Research Projects Agency (DARPA). Previously, he had served as Deputy Director of DARPA's Tactical Technology Office, where he oversaw UAV programs. Prior to that he was deputy director of technology for the Office of Naval Research's (ONR's) Low Observables Technology Office. Heber was the manager of this set of programs, not the initiator of the ideas for it. The ideas were brought to DARPA from the outside (primarily by Abraham Karem for Amber and then Predator).

21 Drezner, G., et al. (1999). *Innovative Management in the DARPA HAE UAV Program*, MR-1054-DARPA. Santa Monica, CA: RAND Corporation.

Other Key Roles in Program Formation

Dr. Robert Fossum, the Director of DARPA, played a crucial role in formulating a program around the notion of a high altitude, long endurance (HALE) UAV. He initiated DARPA's Teal Rain program that investigated advanced technology concepts for HALE—essentially technology push programs to generate new ideas. One of these programs was Karem's Amber. According to Fossum, he personally supported Amber when the cognizant PM was uninterested in pursuing it.

While DARPA, particularly under Fossum, supported HALE developments, these developments foundered with military service lack of interest until a decade later. In the 1990s DARPA became reengaged with the high-level of interest of OSD and the Joint Chiefs of Staff in implementing UAV-based long endurance ISR capabilities. Notably, many of those pushing for this were experienced in the prior HALE UAV efforts through DARPA in the 1980s. This included Secretary of Defense Perry, and Larry Lynn, who had been Deputy Director of DARPA in the early 1980s and was now Deputy Under Secretary of Defense for Advanced Systems and Concepts. Lynn's position was, in fact, created expressly to achieve a breakthrough in ISR technologies. He and others were convinced that only DARPA could effectively manage the ambitious HALE UAV implementation that would lead to both Predator and Global Hawk being fielded.

Key Insights

Some key lessons from the HALE UAV evolution and development include:

- The concept of UAVs did not originate with DARPA—there had been prior efforts to develop and deploy them. However, military service interests in UAVs were generally short-lived and at critical junctures DARPA was critical in promulgating and refocusing UAV developments.
- DARPA's work in support of UAVs has spanned several decades, starting in the 1970s, but was not continuous. The

programs that eventually led to implemented systems were built upon previous efforts.

- The initial impetus for smaller mini-RPVs came directly from Director of Defense Research and Engineering (DDR&E), John Foster, who encouraged DARPA to take on this new direction.
- DARPA's focus on RPVs corresponded with an OSD level focus on addressing Soviet Bloc (and Chinese) threats by being able to see and hit deep targets and quickly destroy their forces before they could mass for strike.
- DARPA supported development of several enabling technologies essential to overall UAV capabilities including sensors, command and control, structures, which contributed to UAV communication, navigation, targeting.
- DARPA determined at the highest level (DARPA Director) to move away from smaller tactical UAVs (RPVs) to High Altitude, Long Endurance UAVs. This refocusing was supported by inputs from high-level advisory organizations (Defense Science Board) and OSD leadership.
- DARPA leadership generally supported the concept of High Altitude Long Endurance (HALE) UAVs despite the lack of interest of the Military Services. However, the specific HALE concepts were brought to DARPA by individuals (Karem) and firms (Boeing, Ryan Aeronautical, General Atomics).
- DARPA helped to develop a novel, non-standard approaches for development and initial acquisition (the ACTD mechanism) to speed implementation of UAVs.
- Strong high-level (OSD) support for the development, demonstration and deployment of novel HALE UAV defense capabilities outside of standard Service processes were crucial for these new capabilities to gain traction.

Optoelectronics Program[22]

Overview

Optoelectronics at DARPA is generally considered to have started as the optronics program that began in 1984, under John Neff. The program was stimulated by requirements of the Strategic Computing Initiative that DARPA launched in 1983, which required advances in networking and signal processing. In the 1989–1992 period the program was expanded and renamed the Optoelectronics Program, taking advantage of congressionally provided funds for university-industry consortia and university optoelectronic centers. The program started in the Defense Science Office (DSO), but moved to the Microsystems Technology Office (MTO) when that office was established in 1991. The program led to major advances in optical communication, including networks that use "wavelength division multiplexing" (WDM). The program was followed by several additional DARPA programs that made further advances at the component and system level, and in the integration of optical and electronic technologies. The program and its successors are credited with accelerating the development and demonstration of WDM components and systems, encouraging the adoption of technical standards that helped the industry grow rapidly, and creating community of experts who helped North American companies move quickly in WDM.

Context and History of the Program Development

Several influences came together to shape the optoelectronics program. One influence was the increasing importance of high-performance computing and networking. By the 1980s, the U.S. military relied increasingly on advanced information technology and communications for intelligence, battlefield intelligence, and logistics. DARPA had long supported computing and networking technology, including the foundation of the ARPANET and Internet. In 1983 DARPA launched

22 Sources for this section include: interview of Dr. Andrew Yang, by authors March, 2016; Optoelectronics Industry Development Association. (2001). *Creating Bandwidth for the Internet Age*. Washington, DC: OIDA; Block, F. L., and Keller, M. R. (2011). *State of Innovation: The U.S. Government's Role in Technology Development*. New York, NY: Paradigm Publishers.

a Strategic Computing Initiative to advance computing, which included the optronics programs. In 1987, the Reagan Administration proposed a new high-performance computing initiative, including networking, which evolved into the High Performance Computing and Communications Initiative (HPCCI). DARPA volunteered to take the lead in advancing the technology of networking. DARPA expanded its support of the development of experimental networks and the underlying technologies, including optoelectronics.

Another stream of influence was the evolution of optical communications in the telecommunications and computing industries. Optical fiber-based communications had rapidly been expanding in telecommunications, but using only one frequency of light at a time. Since the mid-1970s, researchers considered the possibility of sending multiple streams of light down the same fiber using different wavelengths to increase the data flow through the fiber, known as wavelength division multiplexing (WDM). Early work was done by both the telecommunications industry, led by AT&T and Bellcore, and the computing industry, led by IBM. In the early 1980s, AT&T used an early version of WDM in a pilot system. However, WDM at this time was limited by two problems. First, to transmit signals over long distances, there was a need to amplify the signals along the way, and this required converting optical signals back into electronic signals, then amplifying them, and subsequently reconverting them back to optical signals. This process was very expensive. A second key challenge was converting data streams into and out of wavelength-divided light signals, through multiplexing and de-multiplexing.

In the late 1980s, there were possible solutions to both of these problems. The development of the erbium-doped fiber amplifier provided the means to amplify light signals without having to convert them to electronics. Advances were also made, primarily by IBM, in multiplexing and de-multiplexing the light signals.

While in the late 1980s there was industry interest and capability in these technologies, both the telecommunications companies and computer companies were under stress. Previously, IBM and AT&T had monopoly or near-monopoly positions that allowed them to generously fund R&D. However, the breakup of AT&T and IBM's weakening competitive position led to reduced R&D funding, and neither saw optical communications as a lucrative market.

Another important part of the context was the decline of U.S. competitiveness in information technologies in the 1980s. This led to Congressional concern and interest in expanding investment in key technologies and in supporting industry. In 1990, Congress gave DARPA extra money in the fiscal year 1991 budget to fund a series of industry-university-government R&D consortia. Congress had earlier provided funds for the SEMATECH consortium, in which the Defense Department and the semiconductor industry shared the cost of a project to improve semiconductor-manufacturing technology. Senators such as Jeff Bingaman (NM) were impressed with the early results of SEMATECH, and decided to extend the model to other areas of technology. Congress did not earmark the new money for any particular technologies or projects, but instead left the decision on what projects to fund to DARPA.

The combination of these influences created a situation in which the DARPA program managers believed it was timely to pursue a program to take advantage of the recent advances in component WDM technologies (light amplifiers and multiplexing), in order to make major progress in digital communications systems that would have both defense and commercial benefits.

The program managers put forth a proposal to spend $20 million of this extra FY (Fiscal Year) 1991 money for optoelectronic consortia. DARPA's leaders agreed, and later they added approximately $10 million of regular FY 1992 agency funds to this effort. Three consortia received this initial funding, with a focus on developing experimental WDM systems. These three DARPA-supported projects helped revolutionize optical communications. They included:

- The Optical Network Technology Consortium (ONTC). Bellcore (later Telcordia) led ONTC. Other participants included Nortel, Rockwell, the Hughes Research Laboratory, United Technologies, Lawrence Livermore National Laboratory, Columbia University, and Pacific Bell. ONTC is generally credited with designing the standard systems architecture for long-distance, telephone based WDM fiber networks. Several of the key technical participants in ONTC went on to play roles in a subsequent DARPA project, MONET, discussed below.

- All Optical Network Consortium (AONC). MIT's Lincoln Laboratory led this research program, with participation by Bell Labs, MIT, and Digital Equipment Corporation. AONC drew heavily on earlier AT&T research and on government-funded R&D investments at Lincoln Lab and MIT. Its goal was to create a high-speed fiber-optics architecture that was entirely optical, with no electronic regenerators needed to amplify weak optical signals, and was well suited to handling computer data rather than phone calls.
- IBM. IBM won the third contract and focused on developing its ideas for key components for WDM, particularly multiplexer/de-multiplexer ("mux/demux") devices that take multiple data streams, mix them into the WDM light streams, and separate them out again at the end of the fiber line. IBM built one of the first practical WDM networks.

These three consortia focused on the development of both (1) key WDM devices, such as mux/demux devices, and (2) systems architectures that would enable an entire WDM network to operate. DARPA's office for electronic devices, MTO and its computing office (now the Information Innovation Office) cooperated in funding and managing this program.

In 1991, during the time of these three initial consortia projects, DARPA also began funding university centers in optoelectronics. These generated graduate students trained in the new technology and continued to advance the technology. They focused on improving devices for fiber-optic networks and other applications.

The 1991 Gulf War reinforced Pentagon and DARPA interest in developing new data communications technology, and this interest, combined with the technical successes of the three consortia projects, led to a new DARPA initiative—the Broad Band Information Technology Program (BIT), also known as Global Grid. An important Global Grid project was MONET—the Multi-Wavelength Optical Network Project, which ran from FY 1994 through FY 1999. Led by Bell Labs, AT&T Labs (which formed after most of the original Bell Labs went to Lucent), and Bellcore, MONET extended the work of the earlier ONTC project.

MONET brought together the key people from telecommunications companies, equipment producers, and government users, and developed a realistic and feasible WDM architecture. It also promoted technical standards and created a community of WDM experts.

Background and Role of the Program Manager

In 1989, Andrew Yang, became the program manager. He was hired to replace John Neff who was PM from July 1983 through September 1988, and who had come to DARPA from the Air Force Office of Scientific Research (AFOSR). Yang came from the Hanscom Air Force Base in Massachusetts, which was the Air Force's center for developing and acquiring command and control, communications, computer, and intelligence systems, and is also the location of MIT's Lincoln Laboratory. He was recruited to DARPA by Sven Rooslid, another Hanscom alumni at DARPA. Yang was considering retirement when the opportunity for the DARPA job came up. He left the Air Force and joined DARPA.

Yang changed the name of the program from optronics to optoelectronics, but did not make other major changes initially, and continued to support the development of new optoelectronic devices. When the consortia money became available from Congress, Yang put together a proposal for this, and was successful.

Yang stressed that it is better for a PM not to push his/her own idea, but rather to find the best ideas and push those,[23] arguing that this will result in better ideas and more support for these ideas. He further stressed the importance of being flexible and pursuing more than one path towards the goal. Developing the right program is largely a matter of timing (technology, needs, and funding all coming together). One needs to be able to adapt if new opportunities come up (or new sources of funding appear).

He noted that there are a lot of personal connections between PMs, researchers, and future PMs. Technical communities recognize that it is good to get their people into DARPA to help keep the funding flowing to their community.

23 Interview of Dr. Andrew Yang, by authors March, 2016.

Yang was followed, in 1993, Anis Husain, as well as Robert Leheny, and Brian Hendrickson. Their programs continued optoelectronic consortia (e.g., MONET project) and invested in optical signal processing technologies and integration of optoelectronics and electronics on chips.

Other Key Roles in Program Formation

Congress played a key role in providing funding for the consortia, as well as support for working on projects that have commercial as well as defense benefits.

Industry played a significant role in shaping the program. There was industry interest in establishing optoelectronics consortia by 1989. In 1991, the industry formed the Optoelectronics Industry Development Association to provide an organized voice for industry. DARPA provided funding for OIDA to create technology roadmaps, which in turn provided information to DARPA about important technology needs. Industry played a central role in establishing the consortia that were the center of the program.

There was little direct influence on the optoelectronic program from the military services or headquarters, but there was substantial interaction with the defense research laboratories, and especially the Air Force laboratories, due to the close connection between the DARPA program managers and Hanscom Air Force Base.

Key Insights

In the 1990s, there was strong emphasis on industrial competitiveness through consortia, and DARPA was given funds to support them. DARPA efforts included a focus on community building and standard setting, in addition to making technology breakthroughs. DARPA funded the optoelectronic industry's technology roadmaps and formed research consortia that developed real world WDM architecture.

DARPA supported optoelectronics in some form from at least 1985 to 2005 in a series of projects that built upon, at least in part, previous projects. In this regard, the important role of the program manager is not necessarily coming up with a completely original idea, but rather in understanding what the right program is to advance the field at a particular time. It is important to sense when component advances make advances in systems technology possible. In this case, it was also important that the advances to expand digital communications capacity occurred just as the Internet was expanding, creating demand for increased bandwidth.

At the time of the program, DARPA management was not highly metric-driven. Broad Agency Announcements (which formally announced funding opportunities to the public) were relatively new—established around 1990.

The case also illustrates some of the networks from which DARPA program managers are drawn. In optoelectronics, several of the PMs came from or had particularly strong links with the Air Force technical community.

High Definition Systems[24]

Overview

The DARPA High Definition Systems program was started in 1989 as the High Definition TV program. It was renamed as the High Definition Systems Program in 1990 and continued until 1993. It was started in DARPA's Defense Manufacturing Office. After this office was discontinued in 1991, the program became part of the Electronic Systems Technology Office. The program supported work on a number of display-related technologies, including materials and manufacturing techniques. One novel technology supported by the program, digital mirror projection technology, became a commercial success in electronic projectors, and led to an Emmy Award in 1998 and an Oscar Technical Achievement Award in 2015.[25]

24 Sources for this section include: Interview by the authors of Marko Slusarczuk (DARPA PM—High Definition Systems Program—Defense Manufacturing Office, 1989–1993); Sternberg, E. (1992). *Photonic Technology and Industrial Policy: U.S. Responses to Technological Change.* New York, NY: State University of New York Press, 207–18.

25 Their OSCAR citation read as follows: "To Harold Milligan, Steven Krycho and Reiner Doetzkies for the implementation engineering in the development of the Texas Instruments DLP Cinema digital projection technology. Texas Instruments' color-accurate, high-resolution, high-quality digital projection system has replaced most film-based projection systems in the theatrical environment", http://www.oscars.org/news/21-scientific-and-technical-achievements-be-honored-academy-awardsr.

Context and History of the Program Development

Some key aspects of the context for the HDS (High Definition Systems) programs were that:

1) In the 1980s, the U.S. competitive position in many technology industries, including electronics, appeared to be declining, primarily with respect to Japan. This was a matter of national concern, but also political debate. Democrats, who controlled the Congress, generally advocated a more aggressive government role to help technology industries through R&D, while Republicans, who controlled the White House, were opposed to industrial policies that would support specific commercial industries. SEMATECH (also funded through DARPA), a consortium to help the semiconductor industry and its suppliers, was formed in 1987 with support from both political parties in Congress and the White House.
2) Throughout the mid-1980s, there had been substantial discussion that high definition television would be the next driver of consumer electronics and information technology. Both Japanese and European TV manufacturers were discussing analog standards for the HDTV. U.S. manufacturers had already largely withdrawn from the television market, but some saw HDTV as a way back in. Displays were recognized to be important for a variety of defense applications, but the display industry was also seen as important to maintaining U.S. capabilities in electronics.
3) The U.S. Department of Commerce had considered a program to support HDTV, but this was rejected by the Bush administration as industrial policy. DARPA did not feel limited by this restriction because it could justify support of the technology due to its importance to defense.

DARPA Director Craig Fields initiated the HDTV program. He viewed high resolution displays as critical for defense, but also saw HDTV as important for the U.S. electronics and semiconductor industries. Firms in these industries were viewed as being important to maintain the defense industrial base to produce the technologies the DOD needs.

The one remaining U.S. television maker, Zenith, had contacted DARPA with a proposal for a research project. Craig Fields and others explored this, talked with other companies, and held a workshop on photonics. They started a $30 million program and released a Broad Agency Announcement (BAA) in 1989. It attracted substantial interest, with eighty-seven proposals being submitted.

Background and Role of the Program Manager

Marko Slusarczuk was hired as program manager in 1989 to manage the HDTV program. He came to DARPA from the Institute for Defense Analyses (IDA, a Federally Funded Research and Development Center that serves the Office of the Secretary of Defense, and works closely with DARPA) which he had joined in 1984 as a research staff member after earning an ScD in Materials Science from MIT and a law degree from Boston College Law School and having practiced law.

He was urged to apply to be a PM at DARPA by Ruth Davis, an IDA board member, who recommended him to DARPA Director Fields. Fields had just begun the HDTV program and had an interim PM, but was looking for someone to take it over fulltime. Slusarczuk knew of the program based on a *Washington Post* article and specifically asked that he be its PM, and Dr. Fields hired him for the position.

Slusarczuk was not initially a display technologist, but he had a substantial background in the underlying microelectronics and materials technologies. He stated that his main source of ideas for development came from his interactions with individual companies and academic researchers. Moreover, he had also earned a law degree and understood issues regarding business development. His experience at IDA gave him a perspective regarding defense interests in microelectronics generally. This background helped Slusarczuk see the need to support not just the end-product display technologies, but also the underlying component and materials technologies, which included the highly specialized glass substrates for displays produced by Corning Glass and color filters produced by Brewer Science.

Once hired as PM, Slusarczuk had a high level of autonomy to reshape the program. DARPA had brought in subject matter experts as reviewers from the three military services to assess the proposals that responded to the BAA. These reviewers selected three technologies as inputs that they recommended DARPA pursue: Liquid Crystal Displays (LCDs)—primarily of interest to the Air Force for aircraft cockpits and for use in large screen command centers; Electro-luminescent (EL) displays—primarily of interest to the Army for ground vehicles; and Plasma displays—primarily of interest to the Navy for large ship displays. The reviewers specifically rejected several other more novel display technologies. Slusarczuk reviewed all the submissions to the BAA and the reviews and determined that some of the technologies the reviewers had rejected should be supported. In particular, a proposal that had been rejected was the Texas Instrument (TI) Digital Mirror project, which Slusarczuk decided merited more attention. He consulted with another DARPA PM, William Bandy of the Microelectronics Office, who agreed with him that the digital mirror technology, while risky, had great potential. Slusarczuk funded the TI project as well as the three projects the military services recommended. The funding was not sufficient to fully fund the TI project. Nonetheless, he encouraged TI to proceed and to take on the risk, stating that "DARPA will take on all risks of failure",[26] and thus essentially asserting that TI would be shown as successful. He was able to provide additional funds to TI the following year, and the project was indeed a success. TI further developed the digital mirror technology, which became a commercial success. 80 percent of movie houses and 50 percent of all electronic projectors use the TI technology.

The program was originally focused on High Definition Television (HDTV), which Slusarczuk viewed as too narrow and too commercially oriented (given the political dispute over the appropriateness of DARPA helping commercial industries). He reoriented the program to High Definition Systems (HDS). Fields was removed from the DARPA Director position in 1990 in part due to his disagreement with the Bush White House on DARPA's role in supporting dual-use technologies.

Slusarczuk saw his approach as consisting of (1) providing an overall vision; (2) identifying and filling holes; (3) providing connectivity across the technology area. From his perspective, his role was to seek out potential in what was unproven. Slusarczuk said he saw himself "as the conductor of an orchestra". He was "totally unconstrained" with

26 Interview of Marko Slusarczuk by the authors, March 2016.

no reviews, no specific milestones. He had to demonstrate progress, but was not held to concrete milestones. This flexibility allowed him to adjust program direction as the technologies evolved. He could make decisions without consulting management at each step. He feels that this was the general approach at DARPA at the time.

Regarding how he developed the program, he said he had complete authority within the budget to layout and pursue his research agenda. He mentioned that he even briefed Secretary of Defense Dick Cheney and Chairman of the Joint Chiefs of Staff General Colin Powell without having to review these briefs with anyone at DARPA. He said that today at DARPA that this would be very unlikely.

Management was very hands-off. Slusarczuk stated that he never had to seek approval for any decisions once he became the PM. He informed and consulted with management, but the decision ultimately rested with him. He worked under Michael Kelly, the Director of the Manufacturing Technology Office (MTO) at DARPA.

Slusarczuk said another thrust he took on his own was funding companies to work on underlying manufacturing technologies needed for making advanced displays. This included companies such as Applied Materials, which made production equipment for depositing and etching the amorphous silicon for LCDs, Standish Industries for assembling the glass panels into displays and filling them with the liquid crystal material, and MRS which made lithography equipment for imaging the electronics onto the glass substrates. He supported work on the phosphors needed for plasma displays (Phosphor Center of Excellence at GA Tech, plus individual research efforts to develop blue phosphor). He also conceived an industry consortium (USDC) for providing inputs from display makers on the equipment and materials infrastructure needed.

He encouraged or required participants in his program to work together in a variety of ways. He required university programs that received more than $250,000 from his program to send their principle investigator to a private company working on the DARPA display program to learn what problems commercial firms had in display technologies. He also used annual "information exchanges" in which all participants in his program were required to attend in order to "share and collaborate". During these sessions he said he would hold special meetings with specific participants to encourage linkages between firms based on connections that they might not themselves see. "I could do this because I had knowledge across the program that they didn't".[27]

Other Key Roles in Program Formation

The DARPA Director, Craig Fields, played a key role in establishing the program. There was also strong influence from Congress and the White House. Political sensitivities encouraged the shift from HDTV to HDS.

Congress strongly supported the program, while the White House was initially opposed. With the change from President Bush to Clinton, the White House also strongly supported the program, and enabled additional funding.

Industry also played a role, with early support for a program coming from industry. The idea for the digital mirrors technology, which became one of the most important parts of the program (and perhaps produced the most notable result), came from an industrial proposal in response to the Broad Agency Announcement.

The DOD services had input to the program through their review of proposals in response to the BAA. They each tended to want to continue to support technologies in which they already had some involvement (plasma, LCD, electro luminescent).

Key Insights

In this case, the PM was not the source of the idea for the program, but had a major influence in shaping the direction of the program. The program idea came from the DARPA director, based on his view of what was important to both industry and the defense establishment in the long run. The PMs role was as the conductor of an orchestra and driver of the program; he identified gaps that needed to be filled for the program to succeed. This case also illustrates that sometimes DARPA's originality is not in the idea for the program, but in its ability to support creative ideas within the program (in this case the digital mirror technology).

27 Interview of Marko Slusarczuk by the authors, March 2016.

The PM at that time (and in that office) had a high level of autonomy in this case, and was not required to meet rigid metrics. The case also illustrates the importance of Congressional and Administration politics in some areas of DARPA technology at some times.

Spintronics (Quantum Computing)[28]

Overview

Development of magnetics-based and quantum microelectronics at DARPA was initiated and sustained by program manager Stuart Wolf in DARPA's Defense Sciences Office (DSO) from 1993 through 2005. The Spintronics program developed non-volatile magnetic memory (MRAM) devices and led to SPiNS, a project which sought to develop spin-based integrated circuits (ICs). During this period Wolf started a dozen related programs in the field of magnetics and electron spin for microelectronics. Thus, Wolf exemplifies the role of PM as a program initiator—in fact, he was what might be termed a serial instigator of programs, as he sought to develop and build on the initial ideas into increasingly diverse and complex technology developments.

Context and History of the Program Development

Stuart Wolf became a project DARPA manager in 1993 while he was still at the Naval Research Laboratory (NRL), where he was the Branch Head in Materials research. In that capacity he had provided technical consultation to DARPA's Defense Science Office, specifically to program manager Frank Patten on high temperature superconductivity. High temperature superconducting materials had been discovered in 1987 and DARPA wanted a program in this area. Patten asked Wolf to help put together a program. Thus, Wolf was a government scientific expert who advised DARPA on creating this new program.

In 1993, Wolf informed Patten that he was to take a sabbatical from NRL and was considering going to the National Science Foundation for the year. Patten suggested that Wolf instead come to DARPA as a

28 This section is primarily based on Stuart Wolf, interview with Richard Van Atta, March 2016.

PM—but to do this he would have to come for a minimum of two years. To accommodate Wolf, DARPA agreed for Wolf to be "part-time" an NRL while serving as a DARPA PM.

Wolf had specific ideas on developing his own program at DARPA based on developments in magnetic materials and devices. His branch at NRL had explored various aspects of magnetic materials, including work on how to make magnetic thin films. This research had contributed to the development of Giant Magnetoresistance (GMR) in France and Germany. Wolf's idea was to explore possible applications of GMR structures.

Spintronics

Wolf began what he termed a "super-seedling" with $5 million of funds from the Technology Reinvestment Project (TRP).[29] The participants in this program included IBM, Motorola, Cornell University, and Non-Volatile Electronics (NVE). Since IBM had already been working on GMR sensors for hard drives, this application was eliminated from this project. The seedling led to two results: (1) magnetic sensors, and (2) non-volatile magnetic memory (MRAM). The latter, MRAM, was developed by IBM, Motorola, and Honeywell. The program was explicitly dual-use, as "DOD uses a lot of magnetic memory", but the then current technology—plated wire magnetic memory—was comparatively bulky. The argument was that use of MRAM technology would allow a memory device with 128 Kb capacity, that cost $250,000 and weighed 40 pounds, to be replaced by an MRAM megabyte chip that would cost on the order of $1000. Wolf renamed this program "Spintronics" for SPIN TRansport electrONICS. In an interview with TPI, Wolf noted a couple of additional features of this program: (1) it lasted 10 years; (2) it was cost-shared with industry on a sliding scale in which for the first year the funding was 80 percent DARPA and 20 percent industry. The funding then shifted progressively more to industry (70–30, 60–40, 50–50) so that by the end industry was paying the bulk of the costs.

29 The Technology Reinvestment Project was an in initiative of President Clinton to use defense funds to support dual-use technologies, with the intent of helping the defense-related industries shift to non-defense markets following the end of the Cold War. See Congressional Budget Office. (1993). "The Technology Reinvestment Project: Integrating Military and Civilian Industries", July, https://www.cbo.gov/sites/default/files/103rd-congress-1993-1994/reports/93doc158.pdf

Beyond Spintronics

In the TPI interview, Wolf said that he drew upon his background as Branch Head in electronic materials at NRL to conceive of additional programs for DARPA. One of these was Frequency Agile Materials for Electronics (FAME), which drew on NRL work on superconductivity used in tunable filters. The military application that was the initial focus of this program involved replacing phased arrays that were then controlled using costly diodes. The advantage of "paraelectric devices" resulting from the FAME Program was that they varied continuously and were much cheaper. Initially they were manufactured using ceramic materials processing, but later were made with sputtered thin film processes. Devices based on this technology now are used in cellphones.

Wolf said that the process he went through was very straightforward. He would propose an idea to the Office Director of the Defense Science Office, who was very supportive of his ideas, and then he (Wolf) would "pitch the idea" to the DARPA Director. He said his ideas were generated from his role as a Branch Head at NRL and his own technical reading about advanced electronic materials. For example, his reading of research papers on the prospects for magnetic semiconductors—including one from Japan on a GaMnAs magnetic semiconductor that could be tuned using an electric field—led him to believe that this would create a new opportunity for spin-based ICs, which he pursued in his spintronics program. One program that evolved from this was DARPA's SPINS program (SPin IN Semiconductors).

Wolf also funded a consortium to explore whether it was possible to create gate-defined quantum dots as Qbits. They produced a single electron quantum dot as a Qbit using GaAs. Later this was done with silicon. Wolf decided that, while this was one way to produce a Qbit, there were other approaches that were being developed. He conceived of a project called QuIST—Quantum Information Science and Technology—one of which's goals was to identify the best way to produce Qbits. This project has led to on-going research. Furthermore, Wolf has stimulated other programs for other DARPA PMs. One example is a program on "metamaterials", which his colleague from NRL, Valerie Browning, started when she came to DARPA as a PM. One outcome of this program is negative refractive index materials, which are used in specialized lenses and antennae.

Background and Role of the Program Manager

Wolf is an interesting example of DARPA's varying approach to Program Management. He was recruited by a current PM based on his having supported that PM as a technical advisor for several years. Wolf is an expert on electronic materials, magnetism and related superconductivity—an expertise deriving from his having been a scientist and manager at the Naval Research Laboratory. This background was the basis of his knowledge and connections that permitted him to conceive so many DARPA projects. Thus, he brought to the PM position long-standing expertise in the new field of quantum electronics.

He was brought into DARPA's DSO as an employee of the NRL and stayed at DARPA from 1993 to 2005, being renewed year to year by the DARPA Director. By 2003 the DARPA Director, Tony Tether, decided that, since Wolf was essentially fulltime at DARPA, he should sever his ties to NRL. Tether made special arrangements for this to occur. Wolf retired from NRL and joined the faculty at the University of Virginia, but with the agreement that he would stay "on loan" at DARPA for another two years before going to the university.

Wolf is unusual at DARPA not only for his long tenure, but also for creating a number of different projects: Magnetic Materials Devices, followed by Spintronics, FAME, QuIST, and SPinS. He also started programs in Hard Magnetic Materials called AMPS (Advanced Magnets for Power Systems), SuperHyPE for Superconducting Hybrid Power Electronics, ATM for Advanced Thermoelectric Materials, MO-SAIC for Molecular Observation and Imaging using Cantilevers, FASTCARS for Femtosecond Adaptive Spectroscopic Techniques for Coherent Anti-Stokes Raman Spectroscopy, FLAME, for Femtosecond Lasers for Materials Exploitation, and finally FHOENICS for Femtosecond High Output ENergy Integrated Coherent optical Systems. He was also instrumental in initiating CNID, the Center for Nanoscale Innovation for Defense, which included UCLA, UCSB, UC Riverside, and AMRI, the Advanced Materials Research Institute at the University of New Orleans.

Additionally, Wolf's twelve-year tenure at DARPA exemplifies the fact that DARPA exercises considerable flexibility in its program management—in this case renewing him as a PM for three times the normal four-year assignment.

Other Key Roles in Program Formation

The Spintronics case is one in which the PM played the dominant role in program formation. Wolf drew upon ideas from the scientific literature and through interaction with his colleagues, and program ideas were supported by the DSO office director and approved by the DARPA director.

Key Insights

Dr. Wolf constitutes a clear example of a PM being the initiator of DARPA programs. He had technical expertise in a new field of science and technology and through his NRL management perspective was highly connected to leading research and researchers. He took the lab and university-based research and through industry pushed it into initial implementation.

DARPA provided a venue for Wolf to conceive and grow several programs that took an incipient field from the conceptual research stage to development of practical devices. While this drew heavily on his NRL experience, DARPA provided a means for him to organize ambitious implementation programs involving numerous participants, which was beyond what he could do at NRL.

Wolf's twelve-year tenure at DARPA demonstrates that it is an organization that is flexible even within its own "rules"—such as a PM only being hired for four years.

Personalized Assistant that Learns (PAL)[30]

Overview

The Personalized Assistant that Learns (PAL) program was an artificial intelligence (AI) program run through the Information Processing

30 This section is primarily based on interview of Ray Perrault (co-PI of CALO project), by David Cheney, March 2016.

Techniques Office (IPTO) from 2002 to 2009. It consisted of two projects, the CALO[31] project (managed by SRI International), and the RADAR[32] project (managed initially by Carnegie Mellon University). The PAL program (and specifically the CALO project) is best known for leading to the Siri application on the Apple iPhone, but was also transitioned to the military's Command Post of the Future (CPOF) system.

Context and History of the Program Development

DARPA had funded artificial intelligence since the 1960s, with several cycles of optimism and expansion followed by disappointments and contracting funding. Artificial intelligence had been making progress in several different domains, such as speech recognition, cognition, and machine learning, but there had not been a project that integrated advances across all of these domains and shown what AI could do.

The initial impetus for an initiative came from DARPA director Tony Tether, who wanted to do something in cognitive computing systems—systems that can reason, learn from experience, take advice, explain themselves, and respond intelligently to situations never encountered before.[33] He hired Ron Brachman as the IPTO office director for this purpose. Brachman was leader in the AI community. He had worked at BBN and AT&T Bell labs, and then AT&T technologies. He was highly respected in the community and was very strong in knowledge representation, and he had put together a very strong team at AT&T. Changes at AT&T (cuts in their research programs) had put him on the job market, and Tether was able to attract him to DARPA.

Brachman worked with the community to develop the program. He talked to a lot of people in the community and structured the intellectual area. During these discussions, the concept emerged of doing a large project to bring together the various pieces of AI—speech, learning, cognition, etc., all integrated by a prime contractor. The focus was on developing a virtual personal assistant that could help search for and retrieve information, schedule meetings, make appointments, and so on. The idea for a large project integrated by a prime contractor was

31 "Cognitive Agent (or Assistant) that Learns and Organizes".
32 "Reflective Agents with Distributed Adaptive Reasoning".
33 DARPA. (2003). "DARPA Awards Contract for Pioneering R&D in Cognitive Systems", *DARPA News Release*, 16 July, http://www.adam.cheyer.com/pal.pdf

supported by Tether. This was very different from the typical DARPA program.

They held a workshop with members of the technical community. Since Brachman knew the community, he had a good idea of the capabilities of different groups. It was clear early in the process who Brachman wanted in the program, and Tether took Brachman's word for who should participate. A BAA was released, and the original SRI-led proposal for CALO, based on the discussions at the workshop, was focused on a broad integrative system that combined different elements of AI: vision, natural language, planning, learning, etc. The twenty-page proposal was given to Tether, who rejected it and demanded that it be refocused on learning. So, the focus shifted away from the integration of every part of AI, and towards learning in every part of AI. It was clear that there would be a project, and that it would use the same project team as in the original proposal. However, the focus of the work needed to change in order to focus the program—and specifically the metrics and tests to demonstrate progress—around machine learning. The first year's test would be of the system components, but each component had to focus on learning within that component—e.g., learning in natural language; learning in speech recognition, etc. It was a legitimate and interesting approach, but it was not the only possible approach.

The focus on learning did make it clear and specific. They graphed what the system performance was with learning, versus what it would have been without learning, and it helped to sell the program.

A team led by Carnegie Mellon University won a second smaller project known as RADAR that focused more narrowly on helping managers to cope with tasks such as organizing their email, and planning meetings.

The CALO project had four phases with an evaluation at the end of each. The last phase was focused on technology transition, and so the final phase evaluation was based on how the results were transitioned to different applications. CALO was transitioned into part of the Command Post of the Future, for which General Dynamics was the prime contractor. They also developed a version called "CALO Express" that was created for use by DARPA PMs. It was built and demonstrated, but it never got through DARPA's certification process to be put into their IT system. SRI also used the CALO technologies to develop Siri for mobile phones and spun this off (with venture capital funding) as a new company that was later acquired by Apple.

Background and Role of the Program Manager

The PM, David Gunning, was hired after the BAA was out and proposals had been submitted. He did not have a role in the conception of the program. Gunning had previously been a PM at DARPA, and was the PM for the Command Post of the Future project, which was highly successful. He was brought back to manage PAL. He contributed to the project, but he was not hired for his program ideas—he was hired to manage the program that Tether and Brachman had conceived. He managed it throughout the duration, from 2003–2008. It is not uncommon for DARPA office directors to seek and hire PMs who are able to further develop and execute the Office Director's ideas. PMs are often brought in to manage programs that already exist, and then are expected to develop their own new ideas.

Other Key Roles in Program Formation

The DARPA Director and IPTO Office Director played the key roles in forming and shaping the PAL program project. The Office Director came from the community, and the community shaped the program through workshops. There was less direct influence on the program from DOD.

Because this program was much larger than most DARPA programs, it was visible to Congress and received substantial Congressional oversight due to its size. It was threatened with cancellation by the Congress. However, Brachman and others were able to defend the program so that it continued to receive funding.

Zach Lemnios, Brachman's deputy at IPTO, was also influential in forming the project. He came on board in April 2002. He was very good at managing the bureaucracy and ended up as Assistant Secretary of Defense for Research and Engineering, after going to Lincoln Labs. He subsequently became Vice President, Research Strategy and Worldwide Operations at IBM.

Key Insights

1) PAL was driven from the top down, but was also built on the AI community's perception of what was needed, in an area DARPA had long supported.
2) Some DARPA programs are initiated by DARPA Directors and Office Directors rather than PMs.
3) DARPA sometimes uses a prime contractor, which fills some of the functions of the PM, to integrate different research teams towards a common goal.
4) Some DARPA programs are large enough that they receive Congressional scrutiny.
5) In AI, DARPA support has not been continuous but has come in waves. DARPA provided support for five years or so and then stopped, and then later started another program. The technical community can be significantly disrupted when DARPA stops its funding.
6) A challenge for DARPA is when to decide that it has done enough in an area. This can be when progress is slow, or when commercial entities are getting ready to take over. DARPA used to provide more continuous support for fields.

Topological Data Analysis[34]

Overview

Topological Data Analysis (TDA) was a Defense Science Office program from approximately 2004 to 2008. The program developed data analysis techniques for massive data sets. The program spawned TDA research groups at universities and led to the formation of the Ayasdi software firm in 2008, founded by the DARPA-funded principal investigator (Carlsson) and his graduate or post-doc students. Ayasdi (www.ayasdi.com) which is now a 100+ person, venture capital-funded firm that is conducting data analysis for a large number of clients.

34 This section is primarily based on Mervis, J. (2016). "What Makes DARPA Tick?", *Science* 351/6273: 549–53; and Cochran, D. (2016). Personal Communication with David Cheney, April.

Context and History of the Program Development

Gunnar Carlsson, a Stanford mathematics professor, had developed an interest in the possibility of using topological methods for data analysis. He had been receiving NSF support for "pure math" (math developed under its own logic, without thought of applications) aspects of algebraic topology. Benjamin Mann, a program director at NSF, who had known Carlsson in graduate school (under the same advisor, James Milgram at Stanford), was aware of Carlsson's work and interests. Mann arranged for Carlsson to give a lecture at NSF on possible data analysis applications of topology, and arranged for Douglas Cochran, the DARPA program manager of math programs to attend. Mann and Cochran were co-program managers of a joint NSF-DARPA program. Cochran liked Carlsson's ideas and procured "seedling" funding to get him started as a DARPA investigator. The topic was timely because of the explosion in massive data sets (big data) and the need for new techniques to make sense out of the data, which has applications in intelligence and other areas. Cochran also used the possibility of launching a larger DARPA program in topological data analysis as bait to attract Mann to DARPA. He advised Mann on developing a program that would work in DARPA, so that when Mann met Tony Tether, he already had a fairly well-developed proposal for TDA. The seedling produced impressive results, identifying patterns in a data set that had not been identified through existing methods of analysis. These results allowed Mann to get Tether's approval for the full multi-year program.

Background and Role of the Program Manager

Cochran, the first program manager involved with TDA, is a mathematician who has been on the faculty at Arizona State University since 1989 and who served as a PM at DARPA from 2000 to 2005. He received his PhD in Applied Mathematics from Harvard.

Mann, who became the main program manager responsible for TDA, received his PhD in math from Stanford, had held several tenured academic positions and then became a program officer in NSF's mathematics division. While there, he got to know Cochran when they jointly ran an NSF-DARPA program on "Computational and Algorithmic Representations of Geometric Objects".

Mann arrived in DARPA in June 2004 and stayed until 2010. He started up several other programs, including one to establish fundamental mathematical principles in biology. Upon leaving DARPA, he became a vice president in Ayasdi, the new TDA company.

At the time, new ideas came into DSO in DARPA in a bottom-up fashion. A PM (or potential PM) learned of a compelling technology "push" or DOD need "pull" and developed a program concept around it, promoting it to the DARPA Director. New PMs were expected to come to their job interview with fairly well-developed ideas for new programs. In general, candidates were coached by current PMs and the DSO director before meeting with the DARPA Director, who personally made all PM hiring decisions (often after sending candidates away with additional "homework" questions to answer and then meeting with them again). Current PMs often identified and recruited candidates to become future PMs.

Other Key Roles in Program Formation

The key ideas that enabled the program came from the technical community, especially Carlsson. The DARPA director played a role in approving the program. The recognition that data analysis is applicable to anti-terrorism efforts, a key priority in the post-2001 environment, was an important factor in getting approval for the program.

Key Insights

This illustrates a mode of interaction in the more basic science parts of DARPA. PM-driven projects are an important mode in DSO. PMs who are part of a technical community come to DARPA for the opportunity to do bigger and more aggressive things than they can with NSF or NIH funding. The PMs often have a good idea of the opportunities and the performers.

This case also illustrates that there is some important interaction between NSF and DARPA, including both joint programs and movement of people between the agencies. Some university programs are supported by both agencies. Such programs have been occurring for a long time (several decades).

Furthermore, this case illustrates the close and mutually reinforcing network among researchers and PMs, especially in DSO. PMs come from the research community and often fund researchers who they know and may recruit others from the community to be the next PM. PMs may return to the DARPA-supported research community after serving as a PM.

Revolutionizing Prosthetics[35]

Overview

The Revolutionizing Prosthetics program is intended to produce better prosthetic arms, using advances in robotics and brain-machine interfaces. It began in 2006 in the Defense Sciences Office (DSO), and was transferred to the Biological Technologies Office (BTO) when that office was created in 2014. The program continues today. The program has produced a new prosthetic arm that has been approved by the U.S. Food and Drug Administration (which regulates medical devices). It has demonstrated robotic arms that are both brain-controlled and provide tactile feedback to the brain.

Context and History of the Program Development

The U.S. wars in Iraq and Afghanistan have led to many soldiers (as well as civilians in the local population) losing limbs. This was due in part to improved trauma medical care (and advances in body armor) that allowed many soldiers to survive injuries that would have been fatal in previous wars. Much progress had been made in developing workable prosthetic legs, but developing effective prosthetic arms had been much more challenging due to the many directions of movement and sensitivity of control required of arms and hands.

35 Sources for this section include: Belfiore, M. (2009). *Department of Mad Scientists*. New York, NY: Harper Collins; Burck, J. M., Bigelow, J. D., and Harshbarger, S. D. (2011). "Revolutionizing Prosthetics: Systems Engineering Challenges and Opportunities", *Johns Hopkins APL Technical Digest* 30/3: 186–97; Miranda, R. A., et al. (2015). "DARPA-Funded Efforts in the Development of Novel Brain-Computer Interface Technologies", *Journal of Neuroscience Methods* 244: 52–67.

The private market for prosthetic arms was not large or lucrative enough to drive innovation in prosthetics, and so there was a clear need for DOD investment to give injured soldiers a better life.

Previous DARPA programs, such as the Brain Machine Interface (BMI) program and the Human Assisted Neural Device (HAND) program, had developed techniques to enable direct brain control of computers and use of motor neural signals and sensory feedback for control of appendages or robotic devices. These showed that direct brain control of prostheses could be possible, and that the potential existed for much more sophisticated prosthetic arms.

While driven by a clear military need, Geoffrey Ling, the PM and a physician, is generally credited with creating the Revolutionizing Prosthetics program, motivated by his experiences serving as a military doctor in Iraq and Afghanistan. The DARPA Director, Tony Tether, was also strongly encouraging a program in this area. The goal of the Revolutionizing Prosthetics program was originally to create a neurally-controlled device, packed into the size and weight of a native human arm, that could do most or all of the things expected of a human arm. The program was started in 2006 and led to two main projects. The largest was led by the Applied Physics Laboratory (APL) of Johns Hopkins University. APL led a consortium of more than 30 research institutions and private companies in a project focused on prosthetics controlled by neural impulses, either through noninvasive surface electrodes, more-invasive wireless intramuscular implants, or peripheral nerve or cortical implants.

A second project was started that did not require the same degree of neural integration (requiring no surgery), and with prosthetics that would be controlled by muscular contractions. This project went to DEKA Research and Development (the firm headed by inventor Dean Kamen, who is known for creating the Segway transportation device).

Background and Role of the Program Manager

Ling, the founding PM for the program, was an army colonel and intensive care doctor. He had a PhD in pharmacology from Cornell University and an MD from Georgetown University. He joined the Army and was assigned to the Uniform Services University of the Health

Sciences, the military medical school, where he treated patients, taught medical students, and ran a research lab. He did a neurology residency at Walter Reed Medical Center, and trained in neurocritical care at Johns Hopkins University, with a specialty in caring for traumatic brain injury. He was encouraged to consider DARPA in 2002 from a navy commander and intensive care unit doctor, and he was then recruited by the Director of the DSO, Michael Goldblatt. Ling went on a tour of duty in Afghanistan in 2003, where he saw many civilians and military personnel with limb injuries, and this motivated him to join DARPA to try to develop better technologies for limb injuries. He joined DARPA in 2004 but then was deployed to Baghdad in 2005. When he returned, he started the Revolutionizing Prosthetics program, which requested proposals in 2005 and began in 2006.

After establishing and running the Revolutionizing Prosthetics program and several other programs, he became Deputy Director of the Defense Sciences Office, and then became an Assistant Director in the White House Office of Science and Technology Policy. He later returned to DARPA as the first director of the Biological Technologies Offices (BTO).

Other Key Roles in Program Formation

The program development was clearly influenced by military needs that came out of Iraq and Afghanistan and was also built on prior DARPA projects. The DARPA director, Anthony Tether, was actively involved in hiring Ling, in the decision to fund APL as the prime contractor, and in expanding the program to include the second path that became the DEKA project.

Key Insights

This program is larger (over $100 million) and longer (thus far, ten years) than the typical DARPA project. Like the PAL program, it uses a prime contractor (in this case APL) to integrate a large project consortium. While this model is not the typical DARPA program, it also is not unique (both PAL and Revolutionizing Prosthetics were started when Tony Tether was the director and reflect his influence).

This is an example of a program that was motivated by a clear military need but also shaped by a passionate PM.

Findings, Conclusions, and Key Observations

Process of Program Development

It is clear from these cases that there is no single DARPA program development process. Ideas for DARPA programs come from many places (the technical community, military, advisors, and companies). Programs develop in many different ways, and the process differs by program, over time, and with different DARPA directors. The approach also varies according to:

1) The maturity of the technology (whether a completely new area or one that DARPA has supported before)
2) Whether the technology being developed is at a component or system level; and
3) The political environment at the time (whether non-defense applications are a factor in whether to support the technology).

When discussing DARPA, it is important to be clear about which part of DARPA one is discussing, and which time period. What some may think of as the "standard DARPA model"—with programs initiated and driven by the program manager—better represents the more upstream, science and technology driven parts of DARPA (DSO, BTO, MTO) than the defense systems-oriented TTO and STO. The latter often support larger projects and are more likely to be driven from the top down, as can be seen in the Assault Breaker and Stealth cases.

While there is no single program development process, there are several typical patterns of program development. These can be characterized as follows.

Top down assignment from DOD, OSTP, White House, DARPA director, or others. This was especially common in DARPA's early days, when the focus was on satellites, missile defense, and test ban monitoring, and is more common at the systems level (in the TTO and STO offices), when the goal is to develop a new military system that meets an important defense need. In several cases, the drive for new systems came from the Office of the Secretary of Defense, usually the Director of Defense Research and Engineering, rather than from the military services, which tended to be more resistant to new technology. In some cases, DARPA funded a variety of conceptual studies to generate ideas for programs to meet a military need. In other cases, the DARPA director played an important role in supporting an area of technology that he or she thinks will be useful to the services in the long run (whether the services want it or not).

Programs based on the PM's Idea. There are cases where the PM comes up with the idea, wins support for it, and develops a program. In many cases it is not the PM's idea alone, but rather the PM has successfully drawn ideas from the technical community and used those ideas to form a program. PM-initiated programs appear to be more common in the Defense Science Office and in the more basic technology offices. Many such programs start with a seedling to test their viability. In some cases, a PM may be hired for a specific program. In other cases, they may be hired to implement an existing program (often when the current PM is leaving) and then are expected to develop their own program over the next year or two.

Long-standing thrust areas. Some new programs do not appear to be radically new. In some cases, DARPA has supported a community (e.g., mathematics, optoelectronics, and artificial intelligence) for some time. New programs may be similar to old programs that didn't succeed previously, but for which technology advances have made success more likely. Some programs represent the logical (if aggressive) next steps in a field, and there may be consensus in the community about what the next priorities are. In such areas there is a tension between a desire for continuity and the need for originality. The community wants some continuity of support, while DARPA sees its role as disruptive change that may require the disruption of existing communities. DARPA management feels a need to make sure DARPA's work does not become incremental and inappropriate for DARPA.

Many programs represent a combination of these patterns. For example, DARPA may work on a general problem due to top down interest, such as the need to be able to detect improvised explosive devices better, but the program manager may get ideas from the community through workshops and in responses to a request for information (RFI) or BAA to get the more specific ideas that result in a program.

It is important to note that DARPA programs are often (but not always) preceded by smaller studies. These may be conceptual studies of systems or technical studies to test the viability of a key technology (seedlings).

Roles of Program Managers

There is a variety of kinds of PM, and PMs view their roles somewhat differently. Some PMs are visionaries. Some are idea generators. Some are champions/drivers of other's ideas. Some are facilitator/enablers of communities. Some are hired to manage complex programs that have been conceived by someone else, such as an Office Director or the DARPA Director. Each kind can be successful.

PMs generally have a common role in assembling a program, serving as its champion (advocating the program and overcoming whatever obstacles are in its ways), and managing the program, but the PM may or may not be the source of the idea for the program. Some PMs inherited programs or were hired to manage programs. Some PMs see their role as finding the best ideas from the community and supporting them, rather than originating an idea. Some PMs see their role as conducting an orchestra of contractors.

Many DARPA managers are recruited and recycled through a small community. Many PMs come from and return to organizations such as IDA, SRI, Lincoln Labs, other defense labs, as well as universities that receive DARPA funding. We found that some PMs stay more than the standard three to five years, and some have served multiple assignments at DARPA over decades.

PMs have a variety of backgrounds. They are more likely to have an academic/research background in the upstream offices (DSO, BTO, MTO, I2O) and are more likely to have defense or industrial background in the systems offices (TTO, STO).

The autonomy of PMs has varied substantially over time. At some times, the PMs have had a great deal of autonomy in shaping their programs and have had very little oversight. At other times, especially during the directorship of Anthony Tether, the director was actively involved in shaping many programs.

Additional Observations

The cases we examined illustrate that the key element for the success of a DARPA program is not always the originality of the program. In some cases, a program topic may not be surprising, but the program may generate creative proposals for projects. This was the case for the digital mirror projection system in the high definition systems case, as well as in the prototype UAV. In other cases, the DARPA program may be distinctive not for its program idea but because of its unconventional approach—such as the use of a large-scale industrial consortium or using a prime contractor to integrate university, company, and laboratory research. DARPA's impact may also come from the focus with which an idea (which may have already been supported in a small way by other agencies) is executed. DARPA may achieve greater effects by pursuing an idea with greater funding, more urgency, and more aggressive and specific focus.

In many cases, timing is a key element of success. Part of the art of having a successful program is the ability to sense when science and technology advances at the material and component level have advanced enough to enable advances at the systems level, or to detect when an area of technology is at a state such that a concentrated effort in a specific area can enable a major advance. DARPA does not always get this timing right—there have been cases when DARPA has discovered that the alignment of the necessary factors was not in place and after a time, even as short as a year, either cancelled or redefined a program. Often, however, DARPA learns from these cases and establishes another program when further progress has been made.

While DARPA seeks to be largely independent of politics and acts independently of other agencies, some cases did exhibit the importance of Congressional and White House interaction, especially regarding dual-use technology in the late 1980s and early 1990s. The cases also illustrate how DARPA collaborates with other agencies, such as the National Science Foundation and the Defense Nuclear Agency, on various programs and studies.

One of DARPA's strengths is its flexibility and lack of bureaucracy. On the other hand, this leads to a lack of consistency in processes and to a weak institutional memory. Over the period of the cases in this study, DARPA has evolved towards greater systematization. The institutionalized use of the Heilmeier questions, the use of BAAs and Requests for Information (RFIs) to formally solicit input from a broad range of potential participants, the requirement for customer involvement in programs, and the increased emphasis on achieving specific milestones and metrics all reflect some organizational learning and institutionalization.

Concluding Thoughts

This study suggests that the approaches used to initiate DARPA programs have varied over time and in different parts of the agency. A question for organizations that are interested in adapting some aspects of the DARPA model, is "which DARPA does one want to copy?" There are several candidates. One option would be the "dual-use" DARPA that supported key technologies such as semiconductors and optoelectronics and industrial consortia in the late 1980s and early 1990s. This might be appropriate for organizations that are seeking to strengthen the key industries in their domain.

Another option is to follow the model that is most prevalent in the Defense Sciences Office, which emphasizes developing breakthrough new technologies, based on opportunities created by advances in fundamental science and technology. This model may be most appealing to organizations whose purpose is to create more radical innovation.

The third option would be to follow the model of the Tactical Technology Office and Strategic Technology Office, which emphasizes the development of systems in response to well-articulated needs. This model may be most appropriate for an organization whose mission is to meet a well-defined social need, whether defense or health care.

It may also be useful to consider the evolution of DARPA over time and its interaction with its environment. As the cases have shown, DARPA interacts with a diverse community of researchers and technologists in universities, research laboratories, defense contractors, think tanks and the military, and these can be a source of ideas for programs. This community has co-evolved with DARPA, and is better developed now than in DARPA's early years. Organizations that seek to emulate DARPA, may wish to consider both how to develop this community, as well as how to operate before such a community is well-developed. It may be that DARPA's early days, rather than its current state, provide a more useful model for new organizations.

All of these considerations suggest that, rather than copying a single model of DARPA's processes, it may be wise to emulate DARPA's flexibility and adaptiveness, giving freedom to the Director, and subsequently to the Office Directors, to choose the modalities for initiating programs that appear to be the best for the particular circumstances. In reflection, this is the approach that has worked at DARPA and it is hard to argue against its success.

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