The DARPA Model for Transformative Technologies

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

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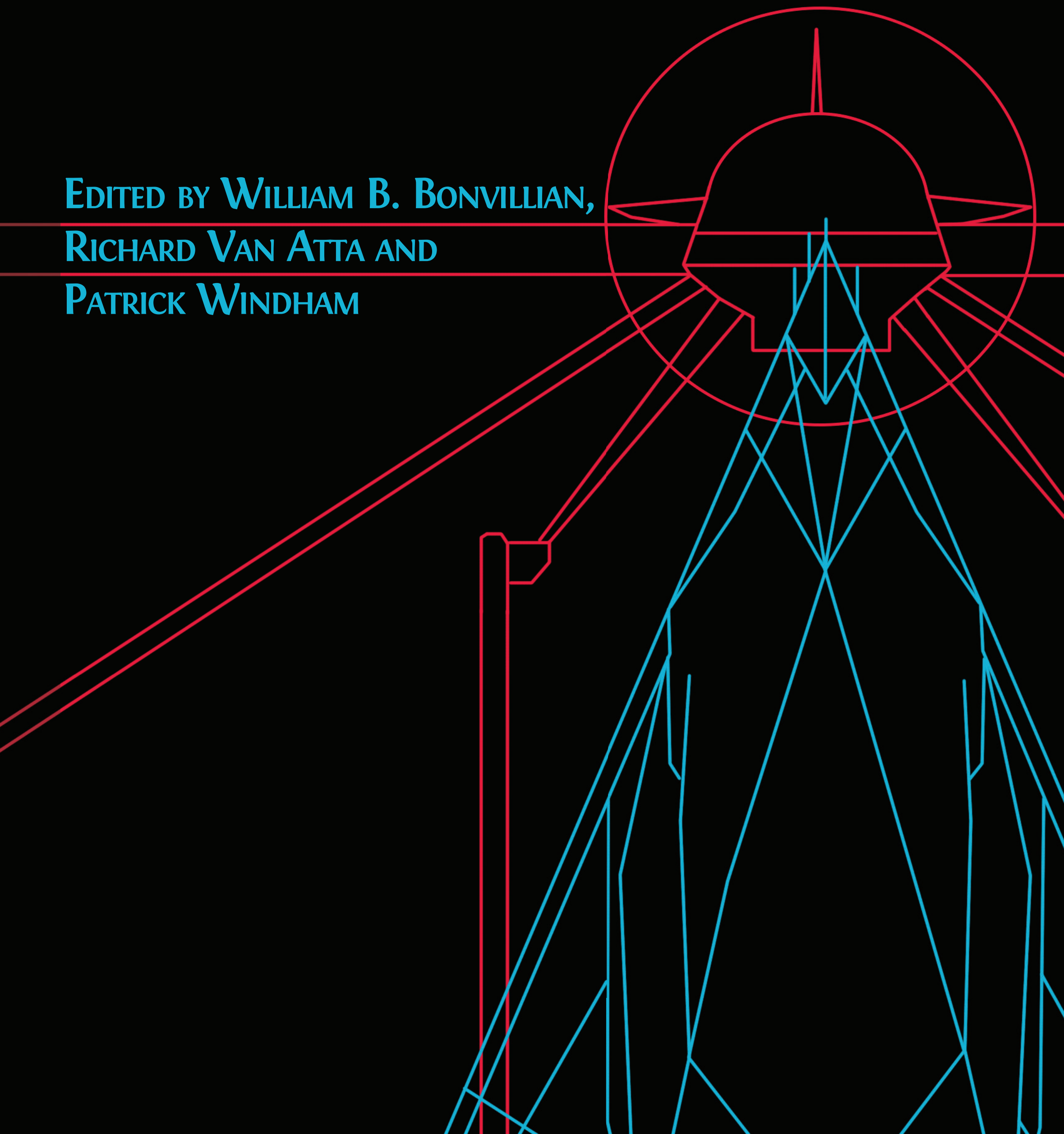

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12. Lessons from DARPA for Innovating in Defense Legacy Sectors[1]

William B. Bonvillian[2]

As World War II grew and the U.S. production machine began to ship war supplies to Britain in every available ship, an enduring transfer was occurring in the opposite direction. The critical moment was in August 1940: British science leader Henry Tizard landed in Halifax and took a train to Washington, leading a small scientific team on a multi-month mission. In a suitcase they carried perhaps the most critical technology of the war: an early prototype of the microwave radar.

However, it was not the technology alone that was so important, but rather, the innovation organization model. The American team, led by industrial organizer and technologist Alfred Loomis and reporting to Vannevar Bush, Franklin D. Roosevelt's science czar, immediately realized the importance of the small radar device, and they also learned about and replicated parts of the system that led the British to operational radar. The essentials were replicated at the Rad Lab at MIT, where microwave radar advances exploded into a galaxy of electronic applications, then transferred to Los Alamos. As explored below, the

1 This paper originally appeared in modified form in 2015 in *The American Interest* 11/1, as "All that DARPA Can Be", https://www.the-american-interest.com/2015/08/01/all-that-darpa-can-be/

2 William B. Bonvillian is indebted to his Georgetown colleague Prof. Charles Weiss for numerous insights behind this article.

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organizational lessons included: form critical innovation institutions, organize them on an "island/bridge" model, create a thinking community, and link technologists to operators.

Thirteen years after the end of the war, these innovation organization lessons were translated directly into the Defense Advanced Research Projects Agency (DARPA), perhaps the most successful federal R&D agency ever. We review a series of questions: what are the foundations of the DARPA model? What is the context of contending innovation models it operates in? What do the four innovation organizational lessons cited above look like up close? DARPA is famous for sponsoring much of the R&D that led to the information technology revolution, innovating in a "frontier" technology sector. However, it has also brought innovations to a "legacy" sector, the conservative military bureaucracy. This kind of innovation is much more difficult because launching it is contested. Moreover, it is rare—legacy sectors rarely undertake disruptive innovations. How did DARPA do this? DARPA's efforts in this legacy territory are much less understood, but because legacy sectors constitute most of the U.S. economy, may provide wider lessons about the landscape of innovation organization.

The Underlying Innovation Models

Like all R&D agencies, DARPA has an organizational genealogy. Initially, then, we turn to the fundamentals—four models for how innovation is organized in the U.S. to put the DARPA model into the larger context.

The most familiar U.S. innovation model evolved in the immediate postwar; it is the so-called *pipeline* or linear model, developed by Vannevar Bush.[3] It holds that basic research operating at the frontiers of knowledge and supplied by government research investment leads to applied research and development. This, in turn, leads to invention, to prototyping, and, finally, to innovation and corresponding broad commercialization or deployment.

While subsequent literature showed that this process wasn't really linear—technology influenced science as well as the other way

3 Bush, V. (1945). *Science: The Endless Frontier*. Washington, DC: Government Printing Office, https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm

around[4]—"pipeline" is still the term generally associated with this technology supply approach.

The World War II-era success of atomic energy, radar, and other technologies, derived from advances in fundamental scientific knowledge,[5] inspired the model; it led to a host of technology advances.[6] It is a "technology push" model, with the government supporting initial research with only a limited role in pressing these advances toward the marketplace. Therefore, it is inherently a disconnected model, with researchers separated from industry implementers.

The second of these models is the so-called induced innovation concept explored by economist Vernon Ruttan[7] in which technology and technological innovation respond to changes in the market, generally to market niche opportunities and price signals. It is typically industry led. New products in this model often generate from modifications of existing technologies to meet new market needs—incremental advances—rather than emerging from basic research. This model involves "technology pull"—the marketplace pulls technology innovations from firms toward implementation in the market.

The third model, which is a variation of the first, can be called the "extended pipeline", a new term. This model enabled many of DARPA's greatest successes. It describes the role of the U.S. Defense Department (DOD), which could not live with the inherent inefficiency of the pipeline model, where the innovation institutions are disconnected. In this model, DOD not only funds the early stages of research, but also sponsors the follow-on stages. To obtain the technologies it requires to meet national security needs, DOD often will fund the research, the development, the prototype, product design, the demonstration, the

4 Stokes, D. E. (1997). *Pasteur's Quadrant, Basic Science and Technological Innovation*. Washington, DC: Brookings Institution Press, 1–25, 45–89.

5 Buderi, R. (1997). *The Invention that Changed the World*. Sloan Technology Series. New York, NY: Simon & Schuster.

6 National Research Council. (1999). *Funding a Revolution: Government Support for Computing Research*. Computer Science and Telecommunications Board. History, Commission on Physical Sciences Mathematics and Applications. Washington, DC: National Academy Press, 85–157 (chapters 4–5), https://doi.org/10.17226/6323, https://www.nap.edu/catalog/6323/funding-a-revolution-government-support-for-computing-research,; Waldrop, M. M. (2001). *The Dream Machine: J. C. R. Licklider and the Revolution that Made Computing Personal*. New York, NY: Viking Press.

7 Ruttan, V. (2001). *Technology Growth and Development: An Induced Innovation Perspective*. New York, NY: Oxford University Press

testbed, all the way to funding implementation and serving as the initial market. Important parts of the information technology revolution—the Internet for example—were developed in this way, but this development was not unique.

Ruttan has noted how DOD also led aviation, electronics, space, nuclear power and computing using this model.[8] These constitute most of the major technology innovation waves of the twentieth century. This model links the initial research stage with a governmental role in the follow-on technology development stages, connecting the institutional actors that dominate each. Agriculture and space advances also employ the extended pipeline, and other R&D agencies are starting to emulate this more connected system.[9] Unlike the pipeline model, it operates at all stages of innovation, not simply the early stages.

The fourth model of innovation dynamics, "manufacturing-led" innovation, describes innovations in production technologies, processes and products that emerge from expertise informed by experience in manufacturing. This is augmented by applied research and development that is integrated with the production process. It is typically industry-led, but with strong governmental industrial support. While countries like German, Japan, Taiwan, Korea and now China have organized their economies around "manufacturing-led" innovation systems, the U.S. in the postwar period did not. It is a major gap in the U.S. innovation system. This system gap is now starting to affect the ability of DARPA and other R&D agencies to translate their technologies into actual innovation.

When the U.S. was constructing its innovation system in the postwar period, it paid little attention to manufacturing-led innovation. This had been the U.S.'s innovation strength since the nineteenth century; it had created the mass production system that had played a central role in winning World War II. Production was not the problem, since the U.S. dominated it. Instead, the U.S. focused on its research system, the front end of innovation, which had emerged at scale during the war, but needed to be retained and augmented. This was the system

8 Ruttan, V. W. (2006). *Is War Necessary for Economic Growth? Military Procurement and Technology Development*. New York, NY: Oxford University Press.

9 Bonvillian, W. B. (2013). "The New Model Innovation Agencies: An Overview", *Science and Public Policy* 41/4: 425–37, https://doi.org/10.1093/scipol/sct059, https://academic.oup.com/spp/article-abstract/41/4/425/1607552?redirectedFrom=fulltext

Vannevar Bush, as President Roosevelt's science advisor, focused on. Others countries, such as Germany and Japan, emerging from wartime chaos, had to concentrate on rebuilding their industrial bases, and thus developed and extended their manufacturing-led innovation systems. As their economies emerged, Taiwan, Korea and China needed to build their industrial bases, and also followed the manufacturing-led innovation path.

Innovation Organization

These first four models exist and can be seen at work at varying degrees of efficiency in the U.S. economy. The fifth model, which can be termed *innovation organization*, is more a conceptual framework that includes the other three and builds on them. It is not a subject in the innovation literature.[10] However, innovation requires not only technology supply and a corresponding market demand for that technology, but also organizational elements that are properly aligned to link the two. There must be concrete institutions for innovation, and organizational mechanisms connecting these institutions, to facilitate the evolution of new technologies in response to the forces of technology push and market pull. This fifth element is essential in our innovation framework: the idea that innovation requires organizations anchored in both the public, academic and private sectors, to form the new technology and to launch it, if innovation theory is to be practical, creating both ideas and means to actually implement them. The focus in the science policy literature is on idea creation; detailed evaluation of implementation is largely ignored.

In other words, while the first four innovation models—pipeline, induced, extended pipeline, and manufacturing-led—are descriptive of existing ways of organizing innovation in the U.S., they are limited in their reach. The fourth provides the organizing methodology that

10 Bonvillian, W. B. (2009). "The Connected Science Model for Innovation—The DARPA Model", in *21st Century Innovation Systems for the U.S. and Japan*, ed. S. Nagaoka, M. Kondo, K. Flamm, and C. Wessner. Washington, DC: National Academies Press. 206–37, https://doi.org/10.17226/12194, http://books.nap.edu/openbook.php?record_id=12194&page=206 (Chapter 4 in this volume); Weiss, C. and Bonvillian, W. B. (2009). *Structuring an Energy Technology Revolution.* Cambridge, MA: The MIT Press, 26–28; Nelson, R. R. (1993). *National Systems of Innovation*. New York, NY: Oxford University Press, 3–21, 505–23.

encompasses the first three and reaches beyond them to the innovation implementation system. It includes the full innovation ecosystem—from research to deployment, but also the forces of culture, political and economic systems, technological routines, and social structures for innovation. This also means the mechanisms and *change agents* needed to surmount the obstacles in that ecosystem to enable innovation. These forces are especially profound in complex, established "legacy" economic sectors—like energy, transport, health care delivery, manufacturing, higher education, agriculture—and also in defense.[11]

These tend to lock in established technologies and resist technology advances that are different from and disrupt their existing economic and technological model. They use political, economic and social systems in their defense against disruptive innovation. By recognizing that there are institutions and mechanisms operating within an innovation system, legacy or otherwise, the innovation organization model enables a richer evaluation of innovation and of potential policies to improve the overall system. The innovation organization model, then, moves beyond the institutional "linkage" idea of the extended pipeline model to embrace a series of elements to provide a bigger picture of innovation: connecting public and private sectors, from research through implementation; merging pipeline and induced innovation, radical and incremental; overcoming structural barriers to innovation particularly relevant to legacy sectors; and consciously embracing change agents.

These five models fit into an historical context. The manufacturing-led model was embodied in the mass production system that the U.S. was the first nation to fully develop, and is also embodied in Japan's quality production system. The pipeline model was inspired by the dramatic advances seen in World War II deriving from basic science, such as nuclear energy from particle physics and electronics from radar advances, in the 1940s-50s. The induced technology model has long dominated industry's role in innovation, with advances derived largely from incremental gains in existing technology, such as, in the 1960s and 1970s, from

11 Bonvillian, W. B., and Weiss, C. (2009). "Taking Covered Wagons East, A New Innovation Theory for Energy and Other Established Sectors", *Innovations* 4/4: 289–94, http://www.mitpressjournals.org/userimages/ContentEditor/1259694503297/Bonvillianinov.pdf; Bonvillian, W. B., and Weiss, C. (2011). "Complex Established 'Legacy' Systems: The Technology Revolutions that Do Not Happen", *Innovations* 6/2: 157–87, https://doi.org/10.1162/inov_a_00075, https://www.mitpressjournals.org/doi/pdf/10.1162/INOV_a_00075

automobiles, consumer electronics and jet aviation. Throughout that era, the kind of innovation described by the extended pipeline model was humming along, bringing out a personal computing and internet revolution in the 1990's after decades of government R&D inputs. While the induced model best fits incremental innovation, the pipeline and extended pipeline models best fit breakthrough or radical innovation. These breakthrough innovations supply the ingredients for waves of innovation that create "frontier" economic sectors that periodically form new parts of the economy. Underlying these developments in technology advance is the innovation organizational model described here and its additional series of elements, vital for understanding our innovation system yet largely unexplored. These innovation organization elements in the model are important in particular for any analysis of the entry of technology innovation into legacy sectors.

Beyond Pipeline

The dominant literature on technological innovation has remained focused on the strengths and weaknesses of the pipeline model, because of the perception that the frontier economy is key to growth. The innovation waves in information technology and biotechnology, for aspects of which the pipeline model provides a description, command most of the analytical focus to date. This pipeline literature has not confronted the problems involved in bringing innovation into established legacy economic sectors. It pays too little attention to how the overall economic and policy environment affects technological innovation in complex networks of both related and unrelated technologies. While the extended pipeline is not a term in the innovation literature, there is some work describing that model,[12] although it is still focused on the frontier economy. The induced technology model often pays too little attention to the governmental role.[13] The literature on induced

12 See, for example, Bonvillian, W. B. (2006). "Power Play, The DARPA Model and U.S. Energy Policy", *The American Interest* 2/2: 39–48, at 40–47, https://www.the-american-interest.com/2006/11/01/power-play/; Alic, J., et al. (1992). *Beyond Spinoff: Military and Commercial Technologies in a Changing World*. Cambridge, MA: Harvard Business School Press.

13 Although Vernon Ruttan was a leading theorist of the induced model, in his last book he turned to an exploration of what we call here the extended pipeline model (Ruttan. (2006). *Is War Necessary for Economic Growth?*).

technology has rested primarily on market pull theory, and on the role of firms in filling technology needs based on changing market signals, ignoring governmental R&D and policy interventions. The two pipeline and the induced models have been viewed as separate and distinct paths; to date none has focused on what is described here as the fourth direction, innovation organization. If we are to adequately describe the framework required for innovation in the range of technologies to be introduced into complex and legacy sectors, the organization model suggests we must combine and integrate the other three models. The systemic barriers to legacy sector innovation also arguably require change agents—institutional and individual actors prepared to push innovations through the sector barriers at each innovation stage.

To summarize, we have described a series of models of innovation. We have noted how they apply to both the frontier as well as the legacy sectors that, combined, make up most of the economy. We have developed a broad new model that encompasses and adds new considerations to the other models to meet the challenge of optimizing the organization of innovation. We have a new framework, then, in which to understand the functioning of innovation systems and the actor institutions that perform within them, including DARPA.

While we placed DARPA in the discussion above within the sweep of the extended pipeline model, it also has developed features that have enabled it to innovate in the legacy defense sector. This means that it represents, as well, key features of what we term the innovation organization model. It is this new way of analyzing DARPA's role that is the primary focus of this article.

First Things First—The Front End of the Innovation System

There is an obvious rule functioning here: no innovations, no innovation system. Innovation requires not only an understanding of the overall system for its development, as set out above, but the first problem concerns the earlier stages of the innovation system where the innovations originate. Later come the problems of overcoming the structural barriers to innovation and creating the linkages between the innovation actors at the subsequent stages of the innovation process, including the role of change agents, where ideas move to implementation. First, however, we must tackle the problem of how to bring about innovation, whether into legacy or frontier sectors. To put the horse before the cart, we must begin with the "front end" of the innovation system, the research, development, prototyping and early demonstration stages.

This means we must move beyond the long-standing focus of pipeline theorists on the valley-of-death stage between research and late-stage development[14] because innovation requires what we can term "*connected science and technology*"—linkages between innovation stages and actors—an integrated consideration of the entire innovation process, including research, development, and deployment or implementation, in the design of any program to stimulate innovation in any complex, established technology sector. As noted, this requires drawing on the two pipeline models, the manufacturing-led model, and the induced innovation model. In addition, we see deep system issues of organization for innovation, because new organizational routines are required across both the public and private sectors to facilitate integrated policies that will support innovation.

These considerations lead to a new approach to innovation policy, aimed at what Avery Sen and others call *transformative innovation*.[15] This transformational task of innovation for both frontier and legacy sectors is usually particularly dependent on the strength of the front end of an innovation system. While, by definition, this will be the case for frontier sectors—which initially require new innovations—it will not always be the case in legacy sectors, where both breakthrough and incremental advances may be needed. For example, in the health legacy sector, incremental advances in electronic medical records could lead to dramatic improvements in the health care legacy sector, although breakthrough medical devices and nanoscale drug delivery are also required. Or, in

14 Branscomb, L., and Auerswald, P. (2002). *Between Invention and Innovation, An Analysis of Funding for Early-State Technology Development*. NIST GCR 02–841. Washington, DC: National Institute of Standards and Technology, 2, https://link.springer.com/article/10.1007%2Fs10961-011-9223-x

15 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, at 470, https://link.springer.com/article/10.1007%2Fs10961-011-9223-x; https://doi.org/10.1007/s10961-011-9223-x; Sen, A. (2014). "Transformative Innovation: What 'Totally Radical' and 'Island-Bridge' Mean for NOAA Research", PhD thesis, George Washington University, Washington, 18–56.

the energy legacy sector, "smart" devices are evolving incrementally for the electric power grid, even if technology breakthroughs in power electronics are needed as well. Other legacy sectors, such as defense or advanced manufacturing, require more breakthroughs. In this way, the legacy sector transformational task will be both breakthrough and incremental, pipeline and induced. Regardless, we need to focus in depth on understanding and strengthening the front-end system; otherwise, creation of frontier sectors and transformation of most legacy sectors will be largely curtailed.

Strengthening the Front End

Strengthening the "front end" of the innovation system requires an innovation capability analysis of the research development, prototyping and early demonstration elements, and of the institutions that support them. Is the system capable of generating the innovations required to bring change to complex and legacy sectors? A series of evaluations is needed, and may require implementing system improvements. Since the front end of innovation is typically driven, initially, by the pipeline or extended pipeline models, we must consider these and their application to the optimal innovation organization approach required in taking this first step.

A series of factors for consideration in this step are reviewed below, and the application of each to DARPA is discussed.

1) *Form critical innovation institutions.* If R&D is not being conducted at an adequate scale by talented researcher teams, innovations will not emerge. However, talent alone is not enough—talent must be operating within institutional mechanisms capable of moving technology advances from idea to innovation. C*ritical innovation institutions* represent the space where research and talent combine, where the meeting between science and technology is best organized. Arguably, there are critical science and technology institutions that can introduce not simply inventions and applications, but significant elements of entire innovation systems.[16]

16 Bonvillian. (2009). "The Connected Science Model".

This is where DARPA takes center stage, with its history of attracting outstanding research talent, and of spurring remarkable technology advance.[17] In promoting innovations, it has long played within both frontier sectors, through its role in the information technology (IT) wave, and the defense legacy sector, through its role in such defense advances as precision strike, and unmanned aerial vehicles (UAVs). As the most successful U.S. R&D agency operating in the innovation space, and because it represents more of a "connected science and technology" approach than other agencies, our initial focus is on lessons that can be learned from the characteristics of the DARPA model.

Formed in 1958 by President Eisenhower to provide more unified defense R&D in light of the separate, stove-piped military services' space programs that had helped lead to America's Sputnik failure, DARPA became a unique entity, aimed at both avoiding and creating "technological surprise".[18] In many ways, DARPA directly inherited the "*connected science and technology*" (linking science research to implementation stages) and "*challenge*" (pursuing major mission technology challenges) organization models of the Rad Lab and Los Alamos projects stood up by Vannevar Bush, Alfred Loomis and J. Robert Oppenheimer in World War II. Building on the Rad Lab example, it built a deeply collaborative, flat, close-knit, talented, participatory, flexible system, oriented to breakthrough radical innovation. Its challenge model for R&D, moved from fundamental, back and forth with applied, creating connected science and technology, linking research, development, and prototyping, with access to initial production. In other words, it followed an innovation path not simply a discovery or invention path.

However, innovation requires not only a process of creating connected science and challenges at the *institutional level*, it also must operate at the *personal level*. People are innovators, not simply the overall institutions where talent and R&D come together. Warren Bennis and Patricia Biederman have argued that innovation, because it is more

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

18 Discussion drawn from Bonvillian. (2009). "The Connected Science Model", 207, 209, 215.

complex than the earlier stages of discovery and invention, requires "*great groups*", not simply individuals.[19] However, unlike other federal R&D agencies, DARPA has attempted to operate at *both* the institutional and personal levels. DARPA became a bridge organization connecting these two institutional and personal organizational elements.[20]

At the heart of the DARPA ruleset is what Tamera Carleton has termed a "*technology visioning*"[21] process, which appears to be particularly key. It uses a *"right-left" research model*—its program managers contemplate the technology breakthroughs they are seeking to emerge from the right end of the innovation pipeline, and then go back to the left side of the pipeline to look for proposals for the breakthrough research that will get them there. As noted, it uses a *challenge-based* research model—seeking research advances that will meet significant technology challenges. It looks for *revolutionary breakthroughs* that could be transformative of a technology sector. All of these elements go into a process where agency program managers develop a vision of a technology advance that could be transformative, then work back to understand the sequence of R&D advances required to get there. If these appear in range of accomplishment, the agency has processes that allow very rapid project approvals by the agency directors. This technology visioning process is very different from the way industry undertakes step-by-step down-selection of technology options known as the "stage-gate"[22] process, where budget and market gain are factors used to weed out which incremental advances to pursue. The visioning process is also very different from how other federal R&D organizations work; these place more emphasis on research for the sake of research. In the context of attempting to bring innovation into legacy sectors, the visioning process may be particularly apt.

19 Bennis, W., and Biederman, P. W. (1997). *Organizing Genius: The Secrets of Creative Collaboration*. New York, NY: Basic Books.

20 Bonvillian and Van Atta. (2011). "ARPA-E and DARPA", 483–84. See also, on the origins of ARPA-E, Weiss and Bonvillian. (2009). *Structuring an Energy Technology Revolution*, 161–65, 185–86, 206, 260n9, 262nn17–19.

21 Carleton, T. L. (2010). "The Value of Vision in Radical Technological Innovation", PhD Thesis, Stanford University, Palo Alto, http://purl.stanford.edu/mk388mb2729; Bonvillian and Van Atta. (2011). "ARPA-E and DARPA", 485 (italics added).

22 See, for example, Cooper, R.G., Edgett, S. J., and Kleinschmidt, E. J. (2002). "Optimizing the Stage-Gate Process", *Research Technology Management* 45/5, 43–49, https://doi.org/10.1080/08956308.2002.11671532

Other DARPA characteristics enhance its ability to operate at both the institutional and personal innovation organization levels. The following list is largely drawn from DARPA's own descriptions of its organizing elements:[23]

- Small and flexible—DARPA consists of only 100–150 professionals; one can refer to DARPA as "100 geniuses connected by a travel agent".
- Flat—DARPA is a flat, non-hierarchical organization, with empowered program managers.
- Entrepreneurial—DARPA's emphasis falls on selecting highly talented, entrepreneurial program managers, willing to press their projects toward implementation, often with both academic and industry experience. They serve for limited (three- to five-year) duration, which sets the timeframe for DARPA projects.
- No laboratories—DARPA's research is performed entirely by outside performers, with no internal research laboratory.
- Focus on impact not risk—DARPA's projects are selected and evaluated on what impact they could make on achieving a demanding capability or challenge.
- Seed and Scale—DARPA provides initial short-term funding for seed efforts that can scale to significant funding for promising concepts, but with clear willingness to terminate non-performing projects.
- Autonomy and freedom from bureaucratic impediments—DARPA operates outside the civil-service hiring process and standard government contracting rules, which gives it unusual access to talent, plus speed and flexibility in contracting for R&D efforts.

23 This list is drawn from DARPA. (2008). *DARPA—Bridging the Gap, Powered by Ideas*. Arlington, VA: Defense Advanced Research Projects Agency, http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA433949; DARPA. (2003). *DARPA Over the Years.* Arlington, VA: Defense Advanced Research Projects Agency. For a more detailed evaluation of DARPA's ruleset, see, Bonvillian and Van Atta. (2011). "ARPA-E and DARPA".

- Hybrid model—DARPA often puts small, innovative firms and university researchers together on the same project so that firms have access to breakthrough science and researchers see pathways to implementation.
- Teams and networks—at its best, DARPA creates and sustains highly talented teams of researchers, highly collaborative and networked to be "great groups", around the challenge model.
- Acceptance of failure—DARPA pursues a high-risk model for breakthrough opportunities and is very tolerant of failure if the payoff from potential success is great enough.
- Orientation to revolutionary breakthroughs in a connected approach—DARPA is focused not on incremental innovation, but on breakthrough/radical innovation. It emphasizes high-risk investment, moves from fundamental technological advances to prototyping, and then attempts to hand off the production stage to the armed services or the commercial sector.

The above rules are part of the established DARPA culture as a critical innovation institution. But there are other important foundational and underlying features that DARPA has adopted, not as well understood, but more central to building a strong, up front-end innovation system that it exemplifies. These provide broad, overall front-end organization lessons.

2) *Use the island/bridge model.* Bennis and Biederman[24] have argued that innovation requires locating the innovation entity on an "island" and protecting it from "the suits"—the bureaucratic pressures in larger firms or agencies that too frequently repress and unglue the innovation process. Nonetheless, they note that there must also be a "bridge" —the innovation group must also be strongly connected to supportive top decision-makers who can press the innovation forward, providing the needed resources. Sen has argued this is a foundational innovation model.[25]

24 Bennis and Biederman. (1997). *Organizing Genius*, 206. See also, Sen. (2014). "Transformative Innovation", which expands and builds on the Bennis-Biederman concept.

25 Sen. (2014). "Transformative Innovation".

The island/bridge model has been, from the beginning, a key to DARPA's success. Indeed, other innovative organizations use it as well. Lockheed's Skunk Works,[26] Xerox's PARC (Palo Alto Research Center)[27] and IBM's PC project[28] have exemplified island/bridge at the industry level, severing innovation teams from interference from the business/bureaucratic side. As noted in point (4), below, some of the ideas for this approach came from the British in the 1940s. While the Skunk Works and IBM PC groups also had strong bridges back to "mainland" decisionmakers, PARC did not, and exemplifies the need for the bridge. DARPA exemplifies the island/bridge model at the federal R&D agency level.[29] It has initiated innovation in frontier sectors, particularly IT, as noted, where it operated largely outside the Pentagon's legacy systems, working with and helping to build emerging technology private sector firms. It has also worked within the defense legacy system. It has operated as an island there but also used strong links with the Secretary of Defense and other senior defense leaders as the bridge; these Defense decisionmakers helped bridge technology advances from DARPA researchers to the implementing military services.

There are alternative models to the island/bridge model. The "open innovation"[30] approach is well-known, where firms drop reliance on in-house R&D labs and reach out to groups at other, often smaller, firms (through acquisitions, technology licensing or partnerships) or at universities (linking to public sector funded researchers at these institutions and licensing their work or creating collaborations). This is primarily, however, a tool for more mature firms facing global competition and less able to afford in-house R&D, or their rivals attempting to out-compete them. Robert W. Rycroft and Don Kash pose a similar model, and broaden it, arguing that innovation requires "collaborative networks" at a series of levels that must reach outside the organization for a kind of heightened R&D situational awareness, and

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26 Rich, B, and Janos, L. (1994). *Skunk Works: A Personal Memoir of My Years of Lockheed*. Boston: Little, Brown & Company.

27 Hiltzik, M. (1999). *Dealers of Lightning: Xerox PARC and the Dawn of the Computer Age*. New York, NY: Harper Business. 153.

28 Chposky, J., and Leonsis, T. (1986). *Blue Magic: The People, Power and Politics Behind the IBM Personal Computer.* New York, NY: Facts on File.

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

30 Chesborough, H. W. (2003). "The Era of Open Innovation", *MIT Sloan Review* 44/3, http://sloanreview.mit.edu/article/the-era-of-open-innovation

can be less face-to-face and more virtual.[31] Neither approach obviates the need for an originating innovation "great group" applying an island/bridge approach.

3) *Build a thinking community.* A prerequisite for the ongoing success of the island/bridge model is building a community of thought. In science, it is well understood that each contributor stands on the shoulders of others, building new concepts on the foundations of prior concepts. Ernest Walton and John Cockcroft, for example, working at Cambridge's Cavendish Laboratory, built an early particle accelerator using a strong electrical field. They became the first people to split the atom, changing the atomic nucleus of one element (lithium) into another (helium) in 1932.[32] They built on the active work of a host of other contemporary physicists, from the Cavendish's director Ernest Rutherford, to Ernest Lawrence, Merle Tuve, Peter Kapitza, James Chadwick, George Gamow and Niels Bohr, to name only a few. The group at the Cavendish was a remarkable "great group" itself, but it was also part of a powerful *thinking community* that was constantly contributing ideas to each other. This community was exemplified by the forty physicists who attended the 1933 Solvay Conference, half of whom won the Nobel Prize (including Cavendish attendees Rutherford, Walton, Cockcroft and Chadwick).

Building a sizable "thinking community" has also been key to DARPA's success, as a source of contributing ideas but also for talent and political support.[33] Composed of multiple generations of DARPA program managers and researchers working in a field supported by DARPA, at its best this community becomes a group of change agents and advocates. J. C. R. Licklider, a tech visionary of the first magnitude, in his two stints at DARPA brought in a succession of office directors and program managers and built supporting university research teams that initiated a series of multi-generational technology breakthroughs

31 Rycroft, R. W., and Kash, D. E. (1999). "Innovation Policy for Complex Technologies", *Issues in Science and Technology*, https://issues.org/rycroft/

32 Cathcart, B. (2004). *The Fly in the Cathedral.* New York, NY: Farrar, Straus & Giroux.

33 Bonvillian and Van Atta. (2011). "ARPA-E and DARPA", 476–77, 492.

that, over time, led to personal computing and the Internet.[34] Building a thinking community around a problem takes time to evolve, but reaches a density and mass where ideas start to accelerate. For example, in the field of nanotechnology, physicist Richard Feynman arguably initiated the community with a 1959 noted talk entitled "There's Plenty of Room at the Bottom", urging work at the smallest scale where quantum properties operate. In 1981 researcher Eric Drexler published the first journal article on the subject, and by 2000 over 1800 articles using the term nanotechnology had accumulated, showing a thinking community had formed and was starting to accelerate advances.[35]

4) *Link Technologists to Operators.* Another key organizational feature of successful innovation organizations involves connecting the technologists to the operators. This approach perhaps is best exemplified by the relationship between British scientists and the military on the eve of, and during, World War II. In the early 1930s the assumption of all, from the Prime Minister down, was that "the bomber will always get through"—there was no adequate defense to bomber aircraft, which could devastate both military and civilian targets virtually at will.[36] With Hitler building 4000 aircraft in 1935, and with England only a few miles across the Channel from the European mainland, the ramifications of this assumption in the 1930s' appeasement policy were profound.

However, a small group began to investigate whether air defenses could be created. At the behest of the Royal Air Force's (RAF) scientific Tizard Committee, a scientist team, under Robert Watson-Watt (scientist supervisor of a small defense lab) began investigating radio beam technology that became radar. However, the technology alone did not create an air defense against the bomber; extended trial and error testing with RAF pilot teams led by physicist Henry Tizard, Rector of Imperial College, developed the operational routines that enabled the British to maximize the utility of radar technology for air defense and win the

34 Waldrop. (2001). *The Dream Machine*, chapters 2, 5–7, and 466–71.

35 Milunovich, S., and Roy, J. M. A. (2001). "The Next Small Thing—An Introduction to Nanotechnology", Merrill Lynch Industry Comment, 4 September, p. 2, https://www.slideshare.net/tseitlin/intro-to-nanotechnology-merrill-lynch

36 Clark, R. W. (1962). *The Rise of the Boffins*. London: Phoenix House, 23–31.

Battle of Britain.[37] In this way, it was the constant testing and evaluation with air force operators—fighter interceptor pilots and what became ground control groups—that linked the technologists to the operators, using new but demonstrated technology-based operating systems. Tizard, a World War I pilot as well as leading scientist, famously spoke the pilots' language from shared experience, and the experimental regimens he helped devise and the RAF implemented between 1935 and 1938, coupled with continuing incremental improvements in the technology to meet evolving operator needs, changed the course of the war.[38]

Along with Tizard, three members of his RAF committee, A. V. Hill, A. P. Rowe and Patrick Blackett, developed a doctrine for linking scientists and technologists with operators. This became known as Operations Research.[39] This approach used statistical analysis of operations, applying a range of variable technology and operational approaches to find optimal solutions to operational challenges. Operations Research had World War I precedents in optimizing anti-aircraft artillery developed by Hill[40] and was written up by Blackett in 1941 as a chapter in a short edited book entitled *Science in War*, advocating its widespread use by the military.[41] Blackett, as director of Naval Operational Research, subsequently applied the techniques he helped develop to the war against U-Boats, which were threatening to cut off Britain's wartime food and supplies. Research by his team (known as "Blackett's Circus") resulted in dramatic improvements to optimal convoy size and air-sea convoy protection, with a corresponding dramatic reduction in incidences of U-boat ships sinking.[42]

The British approach to applying science in World War II was to isolate and protect its scientists from military hierarchies—the island/bridge approach—but also to integrate them with the military operators when the outcomes of their research appeared promising. Inventing and

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37 *Ibid.*, 33–54.

38 Clark, R. W. (1965). *Tizard*. Cambridge, MA: The MIT Press, 23–48, 105–92.

39 The term "Operational Research" was coined by A.V. Rowe in 1937, while working as assistant director at the RAF radar research and testing center at Bawdsey; "Operations Research" is the American term. Budiansky, S. (2013). *Blackett's War.* New York, NY: Alfred A. Knopf, 87.

40 Clark. (1962). *The Rise of the Boffins*, 8–9.

41 Budiansky. (2013). *Blackett's War*, 117–18.

42 Budiansky. (2013). *Blackett's War*, 113–66, 221–49.

using Operations Research analysis, it found that the scientists must be informed, involved in, and linked to the decision making not just on technology but also on related strategy and tactics. The British model for using scientists, then, was to keep them out of uniform working in separate research centers (from the RAF's radar operational experiments at Biggin Hill and Bawdsey, to the codebreaking at Bletchley Park) as islands, but with strong ties to the mainland—the service operators.

Tizard, leading the 1940 Tizard Mission that brought vital British microwave radar advances to the Americans before they entered the war, spent two months in discussions with American scientists and military that year, including extensive exchanges with science leaders Vannevar Bush and Alfred Loomis.[43] Tizard and his team apparently explained to Bush and Loomis the science organizational model he and other British science leaders had developed.[44] Bush and Loomis ended up creating largely the same island/bridge model in the U.S. with links to operators, implementing it in such famous projects as the Rad Lab for microwave radar advances at MIT[45] and atomic weapons development at Los Alamos.[46] These projects in turn became central to the subsequent organization of post-war U.S. science.

DARPA, in its work on major defense technology advances, also exemplifies an effort to link technologists with operators, to transform operations. Its work on personal computing and the Internet, which shattered the arm's length relationships in mainframe computing between technologists and operator/users, exhibits the same drive to produce technologies that connect with operators. DARPA's Tactical

43 Clark. (1962). *Tizard*, 248–72.

44 MIT's history of the Rad Lab states, that "Running conferences [with Tizard Mission members] continued till October 13 [1940], and by that time practically everybody was agreed that what the program needed was a central laboratory built on the British lines: staffed by academic physicists, committed to fundamental research but committed even more than that to doing anything and everything needed to make microwaves [radar] work." MIT Radiation Laboratory. (1946). *Five Years at the Radiation Laboratory*. Cambridge, MA: The MIT Press, 12, https://archive.org/details/fiveyearsatradia00mass. See also, Clark. (1962). *Tizard*, 265, 267 (Tizard meetings with V. Bush), 268–69 (Mission meetings with Loomis).

45 Conant, J. (2002). *Tuxedo Park: A Wall Street Tycoon and the Secret Palace of Science that Changed the Course of World War II*. New York, NY: Simon & Shuster, 178–289.

46 Bird, K., and Sherwin, M. J. (2005). *American Prometheus, The Triumph and Tragedy of J. Robert Oppenheimer*. New York, NY: Alfred A. Knopf, 205–28, 255–59, 268–85, 293–97.

Technologies Office (TTO) is specifically designed to bring technologies into military tactical systems, using rapid prototyping to transition to air, ground and naval operators.

To summarize the first step of building front-end innovation capabilities, one of the important lessons from DARPA's ability to bring innovation into a defense sector with deep legacy characteristics has been the importance of *critical innovation institutions*. To perform at a critical level, these institutions should attempt to embody a series of characteristics. They should undertake both *"connected science and technology"*—linking science research to implementation stages—and *"challenge"* approaches—pursuing major mission technology challenges. As discussed, and as DARPA exemplifies, innovation requires not only a process of creating connected science and technology and related challenges at the *institutional level*, it also must operate at the *personal level*. The critical stage of innovation is face-to-face not institutional, so while institutions where talent and R&D come together are required, personal dynamics, usually embodied in "*great groups*", are a necessity. The DARPA *"right-left" research model* can be important to reaching the innovation stage, where program managers contemplate the technology breakthroughs they seek to emerge from the right end of the innovation pipeline, then go back to the left side of the pipeline to look for proposals for the breakthrough research that will get them there. This process tends to lead to *revolutionary breakthroughs* that could be transformative of a technology sector. A technology "*visioning*" process at the outset of the effort appears to be particularly key. The approach results in *high-risk but high-reward* projects.

The island/bridge organizational approach for innovation institutions also appears to be important. The innovation team should be put on a protected island apart from bureaucratic influences so it can focus on the innovation process. The strength of the innovation process will also depend on building on forming a solid *thinking community* as a source for ideas and support. Because innovation must span numerous steps from research through initial production, means for *linking technologists to operators* appear to be critical. Again, DARPA, more than any other U.S. R&D agency, exemplifies these approaches.

These rules apply to the important first step of front-end innovation organization. They take in the key features of the extended pipeline model: strong initial research and linkages between researchers and the institutions that can lead an innovation through the later stages toward implementation. But what about the additional issues presented by the innovation organization framework? These include not only the front-end research and the institutional linkages, but also overcoming the barriers to innovation presented within an innovation ecosystem by legacy sectors and the role in that ecosystem of change agents.

In summary, despite its ruleset and the way it exemplifies optimal front-end innovation, DARPA is part of a defense innovation system; it is an entrepreneurial innovator, but *within* DOD. To foster implementation, it must still rely on the military services, and face the legacy pressures they can embody, for the follow-on stages. How DARPA, and its allies, have undertaken this innovation within a legacy sector provides important lessons for the overall U.S. innovation system.

DARPA Innovation within the Defense Legacy Sector

The defense sector has often led U.S. technological advance. Yet historically, militaries have often been the most conservative of organizations, seeking to refight the last war, suppressing innovation in the name of discipline and reliability, and therefore famously subject to technological surprise—Sputnik (which led to DARPA's creation) is a good example. The U.S. military, like all others, exhibits these legacy sector tendencies. However, in the late 1970s, after almost three decades of Cold War, a remarkable effort began in the Defense Department to introduce transformative technologies. That process contains important lessons for innovation organization within legacy sectors.

When Harold Brown became Defense Secretary and William Perry Undersecretary for Defense Research and Engineering (DR&E) in the Carter Administration in 1977, the nation faced a major Cold War dilemma. Starting under Eisenhower and Kennedy, the U.S. had developed a superiority in nuclear weapons and their missile delivery systems that offset Soviet advantages in conventional forces in Europe. However, by the mid-1970s, that advantage had faded, with the U.S. and Soviets in rough parity in these systems. With its deterrence threat eroding, and the Army's capability in decline as a result of the terrible pressures of the Vietnam War, Perry and Brown were deeply concerned about the possible outcome of a conventional warfare confrontation in Europe. Concern about mutual destruction blunted the ability to use nuclear weapons as a deterrent, and the Soviets had built a three-to-one advantage in force levels, tanks, armored fighting vehicles and artillery in Europe. As Perry later put it, "We thought they had a serious intent to use them, to send a blitzkrieg down the Fulda Gap [the anticipated route of the Soviet ground invasion of Western Europe then thought possible]".[47] This imbalance in conventional forces could have forced the U.S. into a situation where it would have had to employ nuclear weapons, with all of their devastating consequences.

Since equaling Soviet force levels in Europe was not feasible, Perry and Brown developed an "offsets" theory as the basis for a new U.S. defense strategy.[48] They decided to achieve parity and therefore deterrence in conventional battle through systematic technological advance in order to offset the Soviet advantage in force levels. They began a process of translating advances in computing, information technology, and sensors, which had been initiated and long-supported by defense research investments, through DARPA in particular, into three areas of advance: stealth, precision strike, and unmanned aerial vehicles (UAVs). These capabilities later became known as the Revolution in Military Affairs (RMA).[49]

How did this RMA come about? Although this revolution suggests the power of DOD's innovation system, it is also possible, as noted, to characterize much of DOD as a legacy sector. The existing military paradigms within DOD are averse to the risk of innovation. In many cases, this group of RMA capabilities was seen as threatening to vested technologies and capabilities and to the officers and their organizations that had spent their careers developing and using them. In each case, the new technologies faced difficulty in obtaining needed investment and support, just like disruptive technologies in civilian firms that are

47 Perry, W. J. (1997). "Perry on Precision Strike", Air Force Magazine 80/4: 75–76, at 76, http://www.airforcemag.com/MagazineArchive/Documents/1997/April%201997/0497perry.pdf

48 *Ibid.*

49 Marshall, A. W. (1993). "Some Thoughts on Military Revolutions—Second Version", DOD Office of Net Assessment, Memorandum for the Record, 23 August, p. 3; Krepinevich, A. F. Jr. (2002). *The Military-Technical Revolution: A Preliminary Assessment*. Washington, DC: CSBA, 3, https://csbaonline.org/uploads/documents/2002.10.02-Military-Technical-Revolution.pdf

organized around older technology—picture clunky electromechanical calculating machines and their support systems at the advent of electronic calculators. Still, in each case, DOD found a way around these legacy challenges, in ways explored below.

DOD does have a series of institutions that can enable a technology to emerge from research into production and procurement. At its best, these can operate as an integrated innovation handoff system. In practice, however, this system can break down, particularly in the links between the military services—the Army, Navy, and Air Force—and the central functions of the Office of the Secretary of Defense. Despite its best efforts to create a connected system that can smoothly incorporate disruptive technology, DOD is, after all, a half-trillion-dollar annual economy dating from 1789, and inevitably has developed significant features of a legacy sector. DOD is dominated by its services, which can have the characteristics of *vested interests defending existing paradigms*, as is typical of all legacy sectors. The services can employ a series of means to assure legacy paradigm dominance, including, to briefly summarize: *budgeting processes* dominated by the services that protect their established technologies, from aircraft carriers to tanks; a *cost structure* that commits DOD long term to these established weapons platforms; service *institutional architectures* that limit cross service collaboration; and established service-led *knowledge/human resources structures* that are heavily hierarchical, service-oriented, and that limit bottom-up ideas.

These, and related characteristics, have led to four major challenges to the defense innovation system: (1) problems in linking innovators (such as DARPA research teams) with service-led implementation; (2) lack of clarity on security threats the nation faces, thereby creating corresponding difficulty in developing department-wide technology strategies (for example, the U.S. currently faces both monolithic and distributed threats); (3) barriers because of defense business practices that curtail innovation, resilience and adaptability (for example, through "Lowest Price, Technically Acceptable" (LPTA) procurement requirements that sacrifice long term value for short term price gains); and (4) too long of an innovation timeline—platform procurements can be twenty-five years or longer, which limits experimentation and the ability to move technological advances into procurement programs. These problems translate into competitive challenges. China, the upcoming peer competitor, currently has some nine jet fighter programs ongoing compared to one in the U.S., and dozens of UAV programs against less than ten in the U.S. Yet in recent decades, the U.S. has been able to overcome comparable problems.

Against this background, we can now explore the legacy sector problems faced by three of the major sets of technologies behind DOD's Revolution in Military Affairs to see how these obstacles to innovation work out in practice within the defense establishment. In each case, DARPA played a critical role, operating, along with key defense leaders, as a change agent, to overcome these structural obstacles.

Stealth Aircraft

Air superiority has been a fundamental doctrine of U.S. defense since World War II.[50] However, Soviet air defense systems by the late Vietnam War were making U.S. aircraft ever more vulnerable. This forced the Air Force to employ vast air armadas of mixed-purpose aircraft, undertaking jamming and electronic counter-measures, chaff dropping, and radar attack, so as to protect a smaller number of attack aircraft that were actually undertaking the strike mission. As early as 1974, discussions began between DOD's office of the Director of Defense Research and Engineering (DDR&E) and DARPA about the need to develop a "Harvey" aircraft (named after the invisible rabbit in the play and film) that would have a greatly reduced radar, infrared, acoustic and visual appearance. The then Director of DDR&E, Malcolm Currie, sent out a memo inviting DOD organizations to develop radical new ideas for such an aircraft. These ideas became known in DARPA, borrowing a term from anti-submarine warfare, as "stealth", and DARPA began to pursue a research agenda around it.

In 1975, a Lockheed engineer, Denys Overholser, located a research paper by the Chief Scientist at the Russian Institute for Radio Engineering on "Method of Edge Waves in the Physical Theory of Diffraction" and realized that from these concepts a computer program

50 This section draws extensively on chapter 1 (on stealth) in Van Atta, et al. (2003). *Transformation and Transition*; and on Rich, B, and Janos, L. (1994). *Skunk Works: A Personal Memoir of My Years of Lockheed*. Boston: Little, Brown & Company, 16–41. The author is indebted to the IDA studies cited for much of the analysis in the three subsections on defense technologies.

could be developed for geometric shapes that would minimize the radar cross section of an aircraft. Lockheed created the program and brought it to DARPA.

DARPA staff understood the importance of the findings, and jumped on them. DARPA Director George Heilmeier, however, insisted that if the concepts were going to become an aircraft, the Air Force would have to take the lead in developing it because developing and buying aircraft was not a DARPA role. Currie supported the stealth approach and used contacts he had built up in the Air Force leadership to try to bring them on board. However, a major Institute for Defense Analyses study found that,

> Air Force support was highly uncertain, as the Air Force saw limited value in a stealthy strike aircraft, given the severe operational limitations that [meant it] would be relatively slow and unmaneuverable, giving it limited air-to-air combat ability, and it would have to fly [only] at night—a far cry from the traditional Air Force strike fighter. There were also competing R&D priorities, most notably the Advanced Combat Fighter program (which eventually became the F-16).[51]

Currie was able to get the Air Force to go along only by securing extra funding for the project, so that stealth development would be in addition to existing Air Force R&D efforts, and, in particular, would not curtail the F-16 program.

William Perry, who succeeded Currie in leading DDR&E, continued to press the stealth program forward because it fit perfectly with his "offsets" strategy. Lockheed's noted "Skunk Works" won the development contract for what became the F-117 strike fighter. Skunk Works used its famous skills in experimentation, flexible problem solving, strong engineering and collaboration to successfully push the F-117 from idea to break-through reality.[52] Northrop, the other defense contractor working in the stealth field, embarked on a follow-on project that became the B-2 stealth bomber. To retain support from a still skeptical Air Force, Defense Secretary Harold Brown made development of stealth aircraft "technology limited" as opposed to "funding limited". In other words, the funding for this secret program was open-ended and was to continue unless a technological barrier emerged.[53] In Desert

51 Van Atta, et al. (2003). *Transformation and Transition. Volume 1*, I–4.
52 Rich and Janos. (1994). *Skunk Works*, 16–41.
53 Van Atta, et al. (2003). *Transformation and Transition. Volume 1*, I–5–6.

Storm, the F-117 enabled the U.S. to obtain air dominance at the outset of the conflict despite being up against the same type of Soviet air defense system that had created such difficulty for U.S.-built aircraft in Vietnam.

Because the services had limited interest in such a radical and different concept that potentially made many of their existing and upcoming aircraft platforms obsolete, stealth overcame the service legacy sector barriers listed above (from powerful vested interests, to cost structure, to institutional architecture to established knowledge/human resource structures) only because of DARPA's highly innovative organizational and technical capabilities, which operated outside the established defense service hierarchies. DARPA, in turn, required support from the highest levels of DOD's civilian leadership, including Secretary Brown and the heads of DDR&E, and from a separate funding stream. Thus, a series of change agents came to bear on the problem, led by DARPA but linked to the DOD senior leadership and to Lockheed, a major defense contractor with its own unique island/bridge innovation organization, its Skunk Works. The Air Force, however, did embrace the technology over time. Interestingly, initial attempts to introduce stealth technology into Navy ship-building—Lockheed's Skunk Works developed the "Sea Shadow"—failed because of Navy opposition for reasons very similar to the Air Force's concerns.[54]

Precision Strike

The mix of defense capabilities known as precision strike developed as part of DOD's focus on the RMA, responding to the confrontation between Cold War forces in Europe. Faced with much larger Soviet forces, William Perry formulated precision-strike objectives as the capability to "see all high value targets on the battlefield at any time; make a direct hit on any target we can see; and destroy any target we can hit".[55] While armies before the RMA had relied on the massed force of as many individual weapons as possible and a few overwhelming nuclear weapons, precision-strike doctrine focused on the ability to both see and select critical high-value targets and to rapidly cripple them in order to break down the enemy's operating capabilities, without major

54 Rich and Janos. (1994). *Skunk Works*, 271–80.

55 Van Atta, et al. (2003). *Transformation and Transition. Volume 1*, IV-35.

casualties on either side and without significant civilian casualties.[56] While the wars Clausewitz wrote about were those between mass armies inflicting mass casualties on a massive scale, the RMA used precision strike to scale this way back.

To achieve precision strike required "joint" efforts between services. Air Force and Navy weapons systems would have to work in intimate coordination with Army systems. This coordination is never easy between rival stovepipes, and weapons procurement itself remains service controlled. Again, DOD's efforts began with DARPA working initially outside the service R&D systems. The "Assault Breaker" R&D program was envisioned to break up any Soviet charge through the Fulda Gap, and was led by a series of related DARPA technological development efforts over many years.[57] Over time, the technologies contemplated in Assault Breaker were modified and evolved into DOD's "1997 Joint Warfighting Science and Technology Plan (S&T) Plan".[58] The precision-strike system came to include JSTARS, a large aircraft packed with powerful radars to "see" much of the battlefield and acquire and track ground targets. These were tied to Army Tactical Missile System (ATACMS) that could hit mobile targets well behind battle lines, as well as to a range of other precision guided missiles and aircraft-launched precision "submunitions" (smaller weapons carried in a missile warhead) and "smart bombs"—all linked to a "Battlefield Control Element" (BETA) to collect and integrate battlefield information.

In summary, the Joint Warfighting S&T Plan entailed a combination of technologies for surveillance, targeting and precision-guided munitions, all resting on earlier DARPA-led advances in information technology. Again, there was service resistance at a number of stages in the implementation process. Leadership from the Office of the Secretary of Defense was required to build and mount the operating systems, and was crucial in pressing for more service "jointness". The retrospective Institute for Defense Analyses study found:

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56 Department of Defense. (1996). *Joint Warfighting Science and Technology Plan*. Washington, DC: Department of Defense (chapter 4, Part B, Precision Force, 1. Definition), https://apps.dtic.mil/dtic/tr/fulltext/u2/a310991.pdf

57 Van Atta, et al. (2003). *Transformation and Transition. Volume 1*, VI.

58 Department of Defense. (1997). *Joint Warfighting* (chapter 4, Part B).

> Perhaps even more important than the testing and developing of specific technologies [led by DARPA] was the conceptual breakthrough in getting the Services to work together across the barriers of roles and missions to attack the Warsaw Pact tank threat. This cooperative approach was resisted by… the Services, but facilitated by parts of the Army because they understood that the Service needed to work more closely with the Air Force to meet the European threat… The Services had other priorities. The Army continued developing and deploying tanks and helicopters and many in the Service did not want to invest in the new missile technology. So too the Air Force. The larger Service had more important acquisitions: the F-15 and F-16, for example. When competing with Service programs, even good new ideas will not get through the system without a powerful advocate—and for a Joint concept as sweeping as Assault Breaker the advocate had best be the Secretary of Defense.[59]

The combination of an innovative entity, DARPA, and pressure from the Secretary's Office constituted the change agents required to get around the legacy sector problems—from vested interests in the services, to cost structure problems through service commitments, to other programs to problems in creating collective action between services—that afflict the defense establishment.

Unmanned Aerial Vehicles

The idea for unmanned aerial vehicles (UAVs) began, and went through limited development stages in both World Wars, as attack devices, before the advent of guided missiles. While there were early Cold War efforts by the Navy and Air Force, with some remotely piloted vehicles (RPVs) used in Vietnam, the Air Force shut down its UAV efforts in 1976 and shifted focus to cruise missiles. Work on a Navy anti-submarine rotor aircraft ("Dash/Snoopy") was undertaken in the late 1960s and used on ships and by Marines in Vietnam, but subsequently the program was terminated.[60] Despite this early history, today's UAVs are pervasive on the U.S. battlefield, including for counter-terrorist operations. They undertake a wide range of roles: reconnaissance (using cameras, sensors and radar), electronic intelligence gathering, long term surveillance, target designation, communications relays, and now, carrying on-board

59 Van Atta, et al. (2003). *Transformation and Transition*. *Volume 1*, IV.

60 The developments discussed in this paragraph are detailed in Van Atta, et al. (2003). *Transformation and Transition*. *Volume 1*, VI–1–11.

weapons, attack on specific targets. The U.S. military is approaching the point where it will have more UAVs than manned aircraft.

Starting in the mid-1970s, DARPA played a key role in developing the enabling technologies that lay behind later UAV success. It funded R&D in sensors, radar, signal location systems, controls, lightweight and low-visibility airframe structures, long endurance propulsion, and new operating concepts. In the 1980s, working with a highly innovative designer, Abraham Karem, and his small company, DARPA also funded a critical UAV technology development program that built and tested the Amber UAV. After initial flight demonstrations, Navy Secretary John Lehman, a UAV advocate, provided support for the program.

However, Amber was terminated in 1990, rejected by the services as not meeting their durability requirements. Nonetheless, the prototypes for Amber pushed the state of the art, developing critical technologies that were fundamental to subsequent development. This was an example of DARPA pushing outside the box of its R&D role and undertaking product development traditionally left to the services. DARPA played a significant role in the development of other UAV prototypes during this period, and the Navy learned lessons from Israeli drones, which were adopted as the "Pioneer UAV" for spotting ship gunfire.[61] However, UAVs were not scaling up. Frustrated with service failures in developing UAV technologies, Congress intervened in 1988 and forced the consolidation of service UAV programs into a joint project office, which led to a third generation of UAV technology.[62]

Following the remarkable performance of RMA technologies in the 1991 Gulf War, the Defense Science Board, the leading DOD technical advisory body, highlighted military problems that could be resolved by improved UAV capabilities. And in the subsequent Clinton administration, the trio of defense and intelligence agency leaders, Secretary of Defense William Perry, Undersecretary of Defense John Deutch, and CIA Director James Woolsey, pushed together for a renewed UAV effort. In cooperation with DARPA, a new "Advanced Concept Technology Demonstration" (ACTD) process was created under Deputy Undersecretary for Advanced Technology (and later

61 Polmar, N. (2013). "The Pioneering Pioneer", *Naval History* 27/5: 14–15.

62 Developments discussed in paragraph detailed in Van Atta, et al. (2003). *Transformation and Transition*. *Volume 1*, VI–11–26.

DARPA Director from 1995–1998) Larry Lynn, to streamline and accelerate defense technology development and management, but with early cooperation with service users. In effect, Lynn, Perry and Deutch created a new process outside of but involving the services to implement new defense technologies, using UAVs to test the approach.

The result was two deployed UAVs, Predator and Global Hawk, both of which proved highly successful. Predator proved its worth in Bosnia, then in Kosovo, in Iraq no-fly zones, and in Afghanistan, where it was also armed with Hellfire missiles, becoming an attack as well as a surveillance system. Global Hawk was developed by DARPA (using its unique "Other Transaction Authority" to waive traditional acquisition laws and requirements in order to speed development) and initially deployed in Afghanistan as a highly sophisticated reconnaissance tool.[63]

The Institute for Defense Analyses study reached several conclusions about the on-again-off-again UAV experience:

> As occurred with [precision strike and stealth], successful demonstration of the technology for RPV/UAVs did not lead to early acceptance and deployment of the vehicles… There were often differences between the expectations of the DARPA [program manager] and those of the Services on performance (unprepared field verses prepared airstrip) and the level of development (proof of principle verses the need for extensive engineering) needed to transition a program. These differences had an impact on the ability of the system to successfully continue into a deployed system… The systems did not fit within the existing force structure and did not have strong service champions. Without better planning they could not survive the budget battles. The developments often did not fit with existing [Service] operations and doctrine.[64]

When UAV programs started, DARPA's role was to transition the technology to the Services after the proof- of-concept stage, with DARPA doing the R&D and the services and industry doing the engineering and development. Then, with the Amber project, DARPA undertook to actually do the development, but the handoff to the services still proved difficult. After two decades of problems, the technology transition mechanism changed to the "Advanced Concept Technology Demonstration" (ACTD), where a new technical transition entity in

63 Developments discussed in this paragraph detailed in Van Atta, et al. (2003). *Transformation and Transition*. *Volume 1*, VI–26–38.

64 *Ibid.*, VI-39.

the Secretary's Office, using DARPA's highly-flexible procurement authority and building in service participation, undertook a more extended process. In effect, a new organizational mechanism was created outside the existing system as a change agent that finally succeeded in getting around the legacy sector problems between the services and the repeated efforts at senior levels of DOD to push innovative technologies.

Change Agents

Innovation does not just happen. Even if the elements cited here for a strong innovation system are assembled, someone or some entity must serve as the catalyst for change; those *change agents* can be persons and/ or organizations. Change agents, like innovation itself, must operate at both the institutional and the personal, face-to-face level. As usual in human affairs, there is no substitute for leadership.

If the front end of the innovation system generally is a prerequisite to innovation in legacy sectors, then the concept of change agent, suggested in the above discussion of DOD's technology advances, is a requirement as well. In this way, the innovation system needs strengthening, including through specific approaches cited here such as critical innovation institutions, island/ bridge organization, thinking communities, and linking innovators to operators. None of these steps alone will implement innovation, particularly in thorny legacy sectors, unless there are institutions and accompanying individuals prepared to act as change agents. DOD in the past has been able to initiate change through (1) competition between services (for example, through competing missile programs), (2) struggles between competing groups in a service (such as between "brown shoe" aviators and "black shoe" battleship sailors in the Navy), or (3) through directives from defense civilian leadership. (such as through the DARPA-led advances noted above). In each, change agents were critical.

To return to an example cited above, the Royal Air Force in the 1930s could be viewed as a legacy sector. Like its German counterpart, it was dominated by an emerging air power ethos led by its bomber force, which was not focused on generating defenses against bombers—a task it considered largely hopeless. It took a defense R&D organization, led by defense scientists under Tizard and others, to take on this assumption.

To bring on the transformative technology innovation of radar, they built a strong research group, made links to political authorities prepared to support the effort, and created a working testing process with fighter pilot operators. Allied with civilian and RAF leaders, as change agents they implemented war-changing technologies and practices.

DARPA led similar changes in UAV's, precision strike and Stealth in similar ways. Nonetheless, here too, change agents were critical. William Perry, allied with DARPA in two different tours of duty at DOD, guided a series of major innovation efforts though the Department. Moreover, he helped initiate a change agent system, putting in place the structures and policies that enable the change agents to do their jobs. Other defense sector examples include Malcolm Currie at DR&E who supported GPS, Stealth and smart weapons in the 1970s, early DARPA Director Jack Ruina, who guided its early contributions, and J. C. R. Licklider, the first Information Processing Technologies Office Director at DARPA and the visionary of personal computing and the Internet. President Eisenhower might rate as change agent for putting DARPA in place, and Herbert York, the first DARPA chief scientist (and first Director of DR&E) for helping to envision its initial structure.

Without such change agents, it is hard to see how innovations, particularly in legacy sectors, can emerge out of the innovation pipeline.

Conclusion: Innovation in the Defense Legacy Sector

The stories of the three core breakthrough technologies behind the Revolution in Military Affairs illustrate that the defense sector has many of the attributes of a legacy sector. However, the important point is that DOD found a way to still put these revolutionary technologies into place and bring on significant innovation. Unlike most legacy sectors where breakthrough and disruptive innovations languish, DOD actually implemented them.

DOD turned out to have two major advantages in managing change in its change-resistant, entrenched legacy sector. First, it developed DARPA, a unique innovation entity aimed not only at radical technological advance but also at innovation as a system and trying to solve profound puzzles surrounding implementation.

DARPA operates outside the pressures of the military legacy sector and was created and designed as a result of Sputnik to bring innovative change to a Defense Department affected by legacy problems. In effect, DARPA (and its allies) came to play the role that Hyman Rickover and his group played for atomic submarines and that Bernard Schriever and his group played for ballistic missiles.

It appears vital, then, to bring front-end innovation capabilities to influence legacy sectors. An important lesson from DARPA's ability to bring innovation into a defense sector with deep legacy characteristics has been the importance of *critical innovation institutions*. These institutions should attempt to embody both "*connected science and technology*"—linking scientific research to implementation stages—and "*challenge*" approaches—pursuing major mission technology challenges. As discussed, innovation requires not only a process of creating connected science and technology challenges at the *institutional level*, but it also must operate at the *personal level*.

The critical stage of innovation is face-to-face, not institutional, so, while institutions where talent and R&D come together are required, personal dynamics, usually embodied in "*great groups*" are a necessity. The DARPA *"right-left" research model* can be important in reaching the innovation stage, where program managers contemplate the technological breakthroughs they want to emerge from the right end of the innovation pipeline, then go back to the left side of the pipeline to look for proposals for the breakthrough research that will get them there. This process tends to lead to *revolutionary breakthroughs* that could be transformative of a technology sector. A technology "*visioning*" process at the outset of the effort appears to be a particular key. The approach results in seeking *high-risk but high-reward* projects.

As discussed, the *island/bridge* organizational approach for innovation institutions also appears to be important. The innovation team should be put on a protected island apart from bureaucratic influences that can ruin it, so that it can focus on the innovation process. The strength of the innovation process will also depend on building a solid *thinking community* as a source for ideas and support. Because innovation must span numerous steps—from research through initial production—the means for *linking technologists to operators* appear to be critical. Finally, *change agents* will be required to move the innovation toward implementation.

Second, DARPA alone was not enough. Unlike most legacy sectors, DOD has an official, the Secretary of Defense, who must by law be a civilian, who can exercise authority to force change. If the Secretary sees the need for a technology shift, he or she can muster the power, despite all the legacy sector checks in the system, to direct it. DARPA has been successful when it ties its technological advance to a senior defense leader in the Office of the Secretary who is prepared to override legacy pressures and be a *change agent*. Of course, DOD faced an additional intense pressure for change—meeting national security needs—but these two characteristics, a strong front-end innovation linked to change agents, remain central.

There are important lessons here for other legacy sectors: a "connected" innovation agency, using the extended pipeline model which is outside the legacy system, and then linked to a source of power that can direct change—a change agent—has proved to be a vital combination in the defense sector's ability to innovate. The longstanding perspective on DARPA has been that its successes have been in the "frontier" sector; it is rightly acclaimed for its foundational role in the IT revolution. But there is a less understood perspective on DARPA that constitutes the other side of the coin: it has brought disruptive, radical innovation into a legacy sector.

In this way, DARPA does not only belong in the "extended pipeline" model; it also has developed features that have enabled it to innovate in the legacy defense sector. This means that it also represents key features of what we term the "innovation organization" model. Legacy sectors use political, technological, economic and social system barriers in their defense against disruptive innovation. The innovation organization model recognizes that there are many institutions and mechanisms operating within an innovation system, particularly in legacy sectors; this mandates a richer evaluation of innovation and of potential policies to shift the overall system. DARPA and its senior Department allies have found ways, delineated above, to impose this richer mix of policies. This mix of strong front-end innovation capability and change agents provides basic lessons for innovation in other legacy sectors that go far beyond defense to other key parts of the economy.

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