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DARPA and its ARPA-E and IARPA clones: a unique innovation organization model

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Abstract

The Defense Advanced Research Projects Agency (DARPA) was formed in 1958 as a research and development (R&D) agency within the US Department of Defense, while the two newer but closely comparable R&D agencies, the Advanced Research Projects Agency-Energy (ARPA-E) and the Intelligence Advanced Research Projects Agency (IARPA), were formed within the Department of Energy (DOE) and the Office of the Director of National Intelligence in 2009 and 2007, respectively. The three share an ambitious innovation organization model, operating as public sector intermediaries between science and industry to pursue mission-oriented, high-risk/high-reward, breakthrough research. They also actively promote the follow-on development and implementation of technologies they support in their mission areas, achieving what has been termed mission innovation. They are therefore much more activist than more standard American R&D agencies, which do not pursue conscious technology strategies oriented to specific mission technology challenges. The three "ARPA" agencies tend to operate as change agents within the often conservative "legacy" sectors they operate within—defense, energy, and intelligence. Within the context of the overall US innovation system, DARPA and IARPA are leading examples of what can be termed the "extended pipeline" model, while ARPA-E is located within a more traditional R&D "pipeline" model agency, the DOE, trying to reach further down the innovation pipeline. All face the types of innovation barriers common to legacy sectors, which further challenge their efforts to implement their innovations. Despite these challenges, this ARPA model has proven quite dynamic; DARPA has an unparalleled record of technological advance, and the other two are rapidly building their own records. ARPA-E and IARPA show that the DARPA model is now a proven one in the innovation space, clearly relevant for consideration in other technology development mission sectors.

JEL classification: L52, O32, O33, O38, O43

The Defense Advanced Research Projects Agency (DARPA) was formed in 1958 by President Eisenhower to provide more unified defense research and development (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 "technology surprise." DARPA is famous for playing critical roles in the information technology (IT) revolution. The DAPRA model for organizing innovation, now copied in other US agencies, is distinct from other innovation agencies around the world in its rejection of "pipeline" and technology "hand-off" approaches used by most agencies. As an innovation organization, DARPA takes responsibility to bring about technological breakthroughs and nurtures them toward to delivering final products. To do this effectively, DARPA has developed a series of specific organizational practices. These have, in turn, been adopted by DARPA clones.

The Advanced Research Project Agency-Energy (ARPA-E) was formed in 2009 to bring a DARPA-like approach to the challenge of advanced energy technologies. The Intelligence Advanced Research Projects Agency (IARPA) began operating in 2007, bringing a DARPA model to development of intelligence-related technologies. These three DARPA models[1] operate as public sector intermediaries, pursuing breakthrough research but also actively promoting its implementation. They are therefore much more activist than the standard American R&D mission agency, acting as change agents within the often conservative "legacy" sectors they serve.

Each of the three "ARPA" agencies has their own quite different policy and mission contexts: defense, energy, and intelligence. DARPA is the largest; its defense mission area is also the broadest. Its funding and area embrace many scientific and engineering fields, from computing to advanced materials to biology, and from both "hard" and "soft" technologies. ARPA-E, in contrast, has only about 10% of DARPA's funding and is focused on energy technologies, emphasizing "hard tech" solutions. IARPA is likewise smaller and more focused on information and computing technologies. All three, however, work to identify major challenges facing their mission areas that could be resolved by developing concrete technology projects. This approach has been termed "mission innovation" (Ergas, 1987; Mazzucato in this issue). All three are oriented to breakthroughs not incremental advances, and all consider the ability of proposed projects to reach actual implementation at a scale that could make a difference on the challenge. Despite their diverse mission areas, all apply a quite similar innovation organization model.

DARPA's critical role in such technology advances as the Internet, wireless transmission advances, Microelectromechanical Systems (MEMS), microprocessor advances, desktop computing, supercomputing, Global Positioning System (GPS), robotics, the "revolution in military affairs" (precision strike, stealth, and drones), synthetic biology, computer simulations and gaming for training, and the driverless car challenge are well understood. ARPA-E and IARPA are much newer and so lack DARPA's 60-year track record. However, both are increasingly recognized for having sponsored highly innovative projects and teams producing promising results, and ARPA-E has issued three detailed impact studies of its results.

This article examines the DARPA model and its variations in ARPA-E and IARPA in detail. It places these agencies it in the context of the overall US innovation system and concludes by noting two structural challenges in that innovation system that they face.

1. DARPA in the context of innovation policy

DARPA was a Cold War creation, formed in response to a technological crisis not from theory. Its operating practices began without any significant inspiration from innovation theorists or growth economists; its early program officers learned by doing. It is only recently—some 60 years later—that innovation theory is catching up and theorizing where an agency like this fits.

The DARPA model, however, can now be understood against an established policy foundation. In recent years it has been seen to occupy a unique place in the context of the US literature on science, technology, and innovation policy, which requires a brief explication here. The economic foundation for the innovation policy field is Robert Solow's work positing technological and related innovation as the dominant causative factor in growth (Solow, 2000). Paul Romer and other new growth theorists argued the importance of technological learning as the underpinning for Solow's technological advance theory (Romer, 1990). These two strands led to an understanding of two basic underlying innovation factors—support for R&D and follow-on technological advance, and support for Romer's concept of human capital engaged in research that lay behind that system. Richard Nelson in turn argued the importance of understanding comparative innovation systems—of assessing the actors in an innovation system and their comparative strengths (Nelson, 1993).[2] We can enlarge this concept to constitute to a third direct

1 The Homeland Security Advanced Research Projects Agency (HSARPA) authorized in 2002 a DARPA entity in the newly formed Department of Homeland Security. However, it was not adequately stood up at the time, and much of its early staff, many from DARPA, left in frustration. The Department's Undersecretary for Science and Technology from 2009 to 2013 worked to reestablish HSARPA during the Obama Administration; because it is, as a practical matter, a more recent clone, this chapter does not attempt to evaluate it.

2 This "innovation organization" factor is also elaborated on at length in Bonvillian and Weiss (2015).

innovation factor, innovation organization, which can be analyzed as a connected system of innovation institutions and organizations. Against these factors, particularly the organizational factor, the US innovation system took shape. DARPA and its clones exemplify a unique innovation organization model within that innovation system that deserves explication.

In the postwar, Vannevar Bush's highly influential "pipeline model" for the postwar organization of US R&D agencies (Bush, 1945) was a "technology push" or "technology supply" model, with government support for initial research but with only a very limited role for government in moving resulting advances (particularly radical or breakthrough innovation) toward the marketplace. Development and the later stages of innovation were left to private industry. Donald Stokes (and others) subsequently sharply critiqued the Bush pipeline model as inherently disconnected, separating the government supported research actors from the industry development actors with few means for technology handoffs between them (Stokes, 1997). Lewis Branscomb and Phillip Auerswald articulated the "valley of death" critique: the disconnect in the US system between research and later stage development led to system failures in commercialization of research results (Branscomb and Auerswald, 2002). This concern has been the major focus of US science and technology policy literature for the past 20 years, with resulting discussions of bridging solutions across this valley. Of course, the pipeline model is not the only US innovation system model.

2. Applying the five models of innovation

Let us examine briefly the five fundamentally different innovation approaches in more detail, which will help us sort out the roles of DARPA and its clones. In essence, as briefly suggested above, there are a series of basic models for the dynamics that drive innovation in different settings: the innovation pipeline, induced innovation, the extended pipeline, manufacturing-led innovation, and innovation organization.[3] These provide a framework for understanding the place in the innovation system occupied by DARPA, ARPA-E, and IARPA. It must also be kept in mind that innovation does not happen entirely through an "invisible hand"; innovation introduction generally requires active efforts by *change agents*. Such agents are particularly critical for innovation in legacy sectors given the significant barriers innovation faces in these sectors. DARPA and its clones are particularly noteworthy as change agents, not simply research organizations.

The *pipeline model*, as noted above, has long dominated US science and technology thinking. It pictures invention and innovation as flowing from investments in research—predominantly from federal basic research support—at the "front end" of the innovation system. Thus, research is dumped into one end of the innovation pipeline, mysterious things occur, industry picks up their development, and new products emerge. Although "pipeline" was not his term, Vannevar Bush is considered the author of this model because he played such a central role in creating it in the early postwar period (Bush, 1945). This model is frequently the origin for major breakthrough inventions. It is a "technology supply" or "technology push" model—government research support supplies the technology which pushes into the innovation pipeline. Here the change agents are the researchers, inventors, and entrepreneurs, not the research agencies themselves, who conceive the technology idea and hand it off to become a breakthrough new product. It serves radical innovation.

But most technology comes from private sector firms that respond to market opportunities, which is a second model, *induced innovation*. Vernon Ruttan is the growth economist who elaborated on this model. "Induced innovation" is the dominant way industry innovates, by identifying market opportunities and then innovating to fill them (Ruttan, 2001). Here, typically the originator—the change agent—is a firm that spots a market opportunity or niche that can be filled by a technology advance—typically an incremental not a radical technology advance. It is a "technology demand" or "technology pull" model—the market creates the demand and pull to induce the technology. Here, the change agents primarily are firms, as well as entrepreneurs and inventors linked to them. Induced innovation in legacy economic sectors (discussed below) can also be affected by policy makers in government and standard setters in industry that can affect market signals and regulatory requirements.

The third model can be termed the *extended pipeline*, where certain US R&D organizations, particularly through the Defense Department (DOD), support moving innovations through every innovation stage. Because DOD could not tolerate a disconnected model when faced with Cold War technological demands, it developed an "extended

3 These models are discussed at length in, Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, 23–30, 181–196, which is drawn from here.

pipeline" (Bonvillian and Weiss, 2015: 181–186). This means support not just for front-end R&D but also for each successive "back-end" stage, from advanced prototype to demonstration, test bed, and often to initial market creation, where DOD will buy the first products (Bonvillian and VanAtta, 2011: 469). This is a mission-oriented innovation approach (Ergas, 1987; Mazzucato in this issue), organized not simply around R&D but toward its implementation. While the government's support role in the pipeline model is disconnected from the rest of the innovation system, in this model it attempts to be deeply connected. Most of the major innovation waves of the past three-fourths of a century have evolved from this system: aviation, nuclear power, electronics, space, computing, and the Internet.[4] The extended pipeline facilitates the bridging of the "valley of death" between advanced research and implemented technology. Here, the change agent includes the governmental entity seeking the advance; DARPA, for example, was a critical change agent for computing and the Internet. DARPA and IARPA are positioned squarely within this model. In general, US innovation models in recent decades have tended to stretch their capabilities further down this innovation pipeline (Bonvillian, 2014: 1093).

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 (Bonvillian and Weiss, 2015: 25, 181–185). This is augmented by applied R&D 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 United States in the postwar period did not. It is a major gap in the US innovation system. This system gap is now starting to affect the ability of DARPA and its clones to translate their technologies into actual innovation.

As will be discussed later in this chapter, when the United States was constructing its innovation system in the postwar period, it paid little attention to manufacturing-led innovation. This had been the US innovation strength since the 19th century; it had created the mass production system that had played a central role in winning World War II. Production was not the problem because in the immediate postwar the United States dominated it. Instead, the United States 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 Vannevar Bush, as Roosevelt's then Truman's science advisor, focused on. Others, emerging from wartime chaos—Germany and Japan—had to concentrate on rebuilding their industrial bases, so 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.

The fifth model, *innovation organization*, is different from the others (Bonvillian and Weiss, 2015: 25–27, 186). It calls for improving the means, methods, and organization of innovation efforts, both on the innovation front and back ends—it is an organizational model. There were suggestions of this from Richard Nelson, who examined the actors in what he and others called national innovation systems (Nelson, 1993); in effect, the strength and capacity of the institutional actors determined the strength of the overall system. He applied his systems idea descriptively; here we use it more dynamically as an organizational threshold. We expand the idea to include examining the connectedness of the network of actors: their ability move technologies to and from each other from research through development stages into full diffusion. In this innovation organization model, the innovation system supports the full innovation spectrum, each stage in the innovation process. While the pipeline model supports R&D at the front-end, and the manufacturing-led model supports the back-end, production stage, the innovation organization model contemplates all stages. It goes beyond the extended pipeline model to orchestrate the institutional and policy changes needed to facilitate innovation not just for a government customer. The other models describe the various existing approaches to innovation; innovation organization describes a different approach, enabling and enhancing innovation by examining a sector's innovation environment, including the institutions and barriers within it, assessing their strengths, evaluating means for improvement, and policies and steps to strengthen the system, fill system gaps, and overcome barriers. Arguably, as discussed below, the complexity and barriers in major legacy sectors, such as energy, manufacturing or defense, require this overall organizational approach; these will not yield to a single innovation dynamic.

Innovation policy theorists, as noted above, have long analyzed the gap between the "front end" of the innovation system—the research side, typically supported by government R&D through university research—and the "back end," the late-stage development through implementation phases, typically a private sector domain. To solve this

4 Although he did not use the term "extended pipeline," Vernon Ruttan wrote about the Defense role in evolving these technologies, Ruttan, (2006).

structural problem, numerous bridging mechanisms have evolved, often with government support. As Philip Shapira and Jan Youtie have noted, this requires technology diffusion approaches and a wide range of institutional intermediaries (Shapira and Youtie, 2016).

DARPA and its clones are not basic research agencies, but public sector intermediaries as well. They work to nurture new technologies from breakthrough stages through applied research and initial development, and then to pass off the technologies to entities that will move them into implementation. They intermediate between finding the breakthrough to technology implementation. As intermediaries, they also operate as change agents.

DARPA is clearly a mainstay of the "extended pipeline" model, reaching toward the unifying "innovation organization" model. But it is also important to note that DARPA was able to succeed because the United States already had a rich and complex publicly funded science and technology system, including the federal labs, university-based labs, the National Science Foundation, and a network of quite significant private sector labs, including, of course, Bell Labs (Gertner, 2012). DARPA could cherry-pick the most promising technologists because there were many of them out there to choose from. However, when the talent supply was lacking or tight, DARPA helped produce more experts—its support for the early computer science departments, for example, proved of deep benefit to the emergence of the field as well as to DARPA's many IT advances. ARPA-E and I-ARPA have played similar talent-intermediary roles in their fields.

But DARPA must play its intermediary role in a defense sector that is often profoundly conservative about technology advances. ARPA-E must be an intermediary in an energy sector that is largely averse to the entry of new technologies. And IARPA faces a comparably conservative intelligence world. These sectors are all complex, established, legacy sectors. The challenge of innovation for intermediaries is already difficult; the difficulty can be multiplied when the technology must be stood up in a legacy sector.

3. The legacy sector challenge for innovation

The rise of IT and biotechnology and the new economic sectors they have created has tended to blind us to the problem of our complex, established, innovation-resistant, legacy economic sectors.[5] This blind spot has helped lead us into a neglected problem: we are limiting our innovation (and therefore growth and therefore job creation). The focus of the field of innovation policy for decades, as noted, has been on the problem of the "valley of death" that creates barriers to frontier innovation. Researchers have failed to focus on a challenge in plain view: How to bring innovation to legacy sectors? We have been after "the next big thing"; this frontier focus is vital but ignores these legacy sectors where the new technology ideas are blocked by deeply entrenched paradigms.

These legacy sectors make up the majority of the US economy. According to recent Bureau of Economic Analysis (BEA) data (BEA, 2013), legacy sectors (utilities, civil construction, energy, building, agriculture, transport, education, health-care delivery, mining, finance, government, education, manufacturing, etc.) make up over two-thirds of US gross domestic product. Add in significant parts of sectors like retail and business services, and the total rises significantly higher. In contrast, the information sector is 4.6% of the US economy.

Some of the nation's greatest needs for innovation now lie in legacy economic sectors that resist innovation that could alter their established technology routines and business models. Prime examples include fossil fuel energy, the electric grid, the health-care delivery system, highway-intensive transport, and input-intensive agriculture.[6] Perhaps at the top of the list is energy because of the climate threat. Also near the top is the manufacturing sector, because of its long-standing role as a job multiplier and its steep decline in the early 2000s. The defense sector's legacy status affects our national security. All these sectors are areas in which innovation can broaden our growth base in addition to frontier-based growth.

Legacy sectors tend to protect themselves from disruption by maintaining a technological–economic–political–social paradigm. That is, they lock in on their existing technologies, driving them toward efficiencies and lower costs that hinder competing new entrants. They lock in on economic and business models that protect their own returns and systems and limit competitor entry. They build systems of political support that lock in policies and subsidies

5 The legacy sector points discussed in this section are explored in depth in Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, which is drawn from here.

6 These sectors are explored in, Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, 67–87, 112–117, 170–176.

that protect their own technologies and systems. And they build social systems that assure their supplies of workers and public support. These obstacles must be addressed if new disruptive innovations are to enter legacy sectors. The technologies behind legacy sectors often work well and will adopt incremental improvements to keep meeting the sector's established requirements. The sector will also adopt new innovations if they further the existing economic model behind the legacy sector. For example, fracking technology fits the legacy fossil fuel sector well. But legacy sectors are not organized to accommodate disruptive new advances that counter elements of the legacy system.

The established legacy sectors share a series of common features;[7] they do not share all these characteristics, but they all share some. Sometimes some or even many of the actors within a legacy sector are interested in embracing change, but they still face the many barriers in the legacy sector that resist change. The point here is that the innovation role of technology intermediaries—including DARPA and its clones—can be frustrated by legacy sector resistance.

The innovation organization model cited above is particularly needed because of the forces at work in legacy economic sectors. 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. Precisely because the DARPA model for innovation organization has demonstrated that it can overcome legacy sector resistance to innovation, it is worthy of close examination.

To summarize, we have described a series of models of innovation. We have noted how they apply to the frontier as well as the legacy sectors that, combined, make up most of the economy. And we have developed a broad new model—"innovation organization"—that encompasses and adds new considerations to the other models to meet the challenge of optimizing the organization of innovation. It is particularly suited to innovation in legacy sectors that require application of most or all the innovation models to advance innovation. In an agency context, it can also be considered an approach for achieving mission innovation to advance technology into implementation. We have a new framework, then, to understand the functioning of innovation systems and the actor institutions that perform within them, including DARPA and its clones.

Basic facts: DARPA, ARPA-E, and IARPA

Agency:	DARPA	ARPA-E	IARPA
Located within:	Department of Defense	Department of Energy	Office of the Director of National Intelligence
Year formed:	1958	2009	2007
Budget, FY18:	$3.12 billion	$353 million	[Not public—intelligence data not released]
Number of program managers—2018:	97	16	27

4. The DARPA model

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.[8] This means that it represents, as well, key features of the "innovation organization" model.

There is an obvious rule here: no innovations, then no innovation system. Innovation requires an understanding of the overall system for its development, but the first problem concerns the earlier stages of the innovation system where the innovations originate. Later comes 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

7 These characteristics are detailed in, Bonvillian and Weiss, *Technological Innovation in Legacy Sectors*, 55–66.
8 This section draws on material in Bonvillian (2015).

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. We must begin with the "front end" of the innovation system, the research, development, prototyping, and early demonstration stages. This requires strengthening this end of the innovation system.

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 (for radar) and Los Alamos projects (for atomic weapons) stood up by Vannevar Bush, Alfred Loomis, and J. Robert Oppenheimer in World War II. Building on the Rad Lab example, DARPA built a deeply collaborative, flat, close-knit, talented, participatory, flexible system, oriented to breakthrough, radical innovation. Its challenge model for R&D linked fundamental with applied, creating connected science and technology, joining research, development, and prototyping, along with access to initial production. In other words, it followed an innovation path not simply a discovery or invention path.

Strengthening the "front end" of the innovation system requires an innovation capability analysis of the research development, prototyping and early demonstration elements, and 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 required 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 first consider the these and their application to the optimal innovation organization approach. A series of factors for consideration in this first 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. But 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 science and technology institutions that can introduce not simply inventions and applications but significant elements of entire innovation systems (Bonvillian, 2009).

This is where DARPA takes center stage, with its history of attracting outstanding research talent and of spurring remarkable technology advances (Van Atta, 2008). In promoting innovations, it has long supported frontier sectors, through its role in the IT wave, and within the defense legacy sector through its role in such defense advances as precision strike, and unmanned aerial vehicles. As the most successful US 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.

However, innovation requires not only a process of creating connected science and challenges at the *institutional level* but 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 Beiderman have argued that innovation, because it requires more linkages than the earlier stages of discovery and invention, requires *great groups* not simply individuals (Bennis and Beiderman, 1997). 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 (Bonvillian and Van Atta, 2011: 483, 484).[9]

At the heart of the DARPA ruleset is what Tamera Carleton has termed a *technology visioning* (Carleton, 2010)[10] process. It uses a *right–left research model*—its program managers contemplate the technology breakthroughs they seek to have 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, and then work back to understand the sequence of R&D advances required to get there. If these appear in range of accomplishment, it has processes that allow rapid project approvals by agency directors. This technology visioning process is different from the way industry undertakes step-by-step downselection of technology options known as the "stage gate" process, where budgets and market gain are factors used to weed out which incremental advances to pursue (Cooper *et al.*,

9 See also, on the origins of ARPA-E, Weiss and Bonvillian (2009).

10 See also, Bonvillian and Van Atta (2011: 485).

2002). The visioning process is also 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.

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 (DARPA, 2003, 2005):[11]

- *Small and flexible*—DARPA consists of only 100 program managers and office directors; some have referred to DARPA as "100 geniuses connected by a travel agent."
- *Flat*—A flat, non-hierarchical organization, with empowered program managers.
- *Entrepreneurial*—Emphasis 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 (3–5 years) terms, which sets the time frame for DARPA projects and assures that new ideas are always coming into the agency.
- *No laboratories*—Research is performed entirely by outside performers, with no internal research laboratory.
- *Focus on impact not risk*—Projects are selected and evaluated on what impact they could make on achieving a demanding capability or challenge.
- *Seed and scale*—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.
- *Hybrid model*—DARPA often puts small, innovative firms and university researchers together on the same project, so 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 tolerant of failure if the payoff from potential success is high.[12]

11 For a more detailed evaluation of DARPA's ruleset, see, Bonvillian and VanAtta, "ARPA-E and DARPA."

12 DARPA's willingness to risk failure to pursue breakthroughs appears to be a particularly significant attribute. It has a record of cancelling failing projects, as well as curtailing and reorganizing them, which supports this position. One researcher has suggested that 85% of DARPA's projects fail to achieve their planned goals (Roland 2010). See, generally, Roland and Shiman (2002: 844, 845; strategic computing program, after over 1 billion invested over a decade, failed to meet most initial program goals). Richard VanAtta, who has studied DARPA from the Institute for Defense Analysis, argues that DARPA, although it makes use of progress milestones, does not impose strict metrics at the outset; its orientation is not process but outcomes. Instead, it actively manages projects, directly involved with the research team, and aimed at significant results that can alter the status quo based on research developments. He argues, for example, that DARPA's Cold War "Assault Breaker" project was not able to realize its initial goal of fully integrated, stand-off precision strike capability but did result in the technologies behind JSTARS and ATACMS that nonetheless delivered breakthrough precision capabilities. VanAtta, R. communication of Nov. 13, 2017. DARPA's active management approach complicates the issue of measuring DARPA success. Erica Fuchs, like other DARPA researchers, argues that DARPA has been successful and that the reasons for the success are replicable and knowable (Fuchs, E. 2009). Roland, supra, argued that such findings rest "on two unprovable assumptions: first, that DARPA has been successful, and second, that the reasons for that success are knowable and replicable. Significant evidence and widespread consensus support both assumptions. But they are assumptions nonetheless." Part of the reason that these are still assumptions is that DARPA looks forward to its next advances, rarely back to its history. As noted, it can also actively reorient its ongoing R&D efforts, as research problems and possibilities evolve. Nonetheless, William Perry, when an Undersecretary of Defense attempting to understand DARPA's innovation role, commissioned an in-depth evaluation of DARPA's role by the Institute for Defense Analysis; the resulting multivolume study documents DARPA's major role in critical technology developments. Van Atta *et al.* (2003). See also, Van Atta (2008). DARPA's critical role in major technology advances, as recounted in the introduction to this article, appears clear.

- *Orientation to revolutionary breakthroughs in a connected approach*: DARPA is focused not on incremental but 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, front-end innovation system that it exemplifies. These provide broad, overall front-end organization lessons.

(2) Use the Island/Bridge model. Bennis and Biederman have argued that innovation requires locating the innovation entity on an "island," protecting it from "the suits," the bureaucratic pressures in larger firms or agencies that too frequently repress and unglue the innovation process (Bennis and Beiderman, 1997: 206).[13] But 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 that this is a foundational innovation model (Sen, 2014).

Island/Bridge from the beginning has been a key to DARPA's success, and other innovative organizations use it as well. Lockheed's Skunkworks (Rich, 1996), Xerox's PARC, Palo Alto Research Center (Hiltzik, 1999), and IBM's PC project (Chposky and Leonsis, 1986) have exemplified Island/Bridge at the industry level, severing innovation teams from interference from the business/bureaucratic side. While the Skunkworks and IBM PC groups also had strong bridges back to "mainland" decision makers, PARC famously did not and exemplifies the need for the bridge. DARPA exemplifies the Island/Bridge model at the federal R&D agency level (Bonvillian and Van Atta, 2011: 486). 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 decision makers helped bridge technology advances from DARPA researchers to the implementing military services.

(3) Build a thinking community. A prerequisite for ongoing success of the Island/Bridge 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. This applies to technology development as well. Building a sizable "thinking community" has been key to DARPA's success, as a source of contributing ideas but also for talent and political support (Bonvillian and Van Atta, 2011: 476, 477, 492).

Composed of multiple generations of DARPA program managers and researchers working in a field DARPA has supported, 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 multigenerational technology breakthroughs that over time led to personal computing and the Internet (Waldrop, 2001: chs. 2, 5–7; 466–471). Building a thinking community around a problem takes time to evolve but reaches a density and mass where ideas start to accelerate.

(4) Link technologists to operators. Another key organizational feature of successful innovation organizations involves connecting the technologists to the operators. DARPA's work on major defense technology advances, like drones, 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, also exhibits the same drive to produce technologies that connect with operators. DARPA's Tactical 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

13 See also, Sen (2014), which expands and builds on the Bennis–Biederman concept.

DARPA exemplifies, innovation requires not only a process of creating connected science and technology and related challenges at the *institutional level* but 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 have 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. 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.

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 implementation 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 US R&D agency has exemplified these approaches.

These rules apply to both the front- and back-end steps of 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 research and institutional linkages but overcoming the barriers to innovation presented by legacy sectors and the role in these sectors of change agents.

Despite the way it exemplifies optimal front- and back-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 embody for the follow-on stages. For example, DARPA, acting as a technology intermediary and change agent, was able to pursue such critical advances as precision strike, drones, and stealth using its "island-bridge" ties to the office of the Secretary of Defense. A succession of Secretaries and senior defense officials, also acting as change agents, worked to press these DARPA-driven technologies into implementation by the military services, despite their initial resistance.[14] Thus, DARPA stretches from the front end of the innovation system deep into implementation, acting as a change agent tied to other change agents at the decision-making level.

5. The ARPA-E model

ARPA-E[15] was first proposed in a National Academies report in 2006 to bring the successful DARPA mechanism to bear on the challenge of needed breakthrough energy technologies (National Academies of Sciences, 2007). Congress, through the leadership of Rep. Bart Gordon, then chair of the House Committee on Science and Technology, authorized ARPA-E in 2007[16] and provided initial appropriations in 2009. It has subsequently received around $300 million in annual appropriations compared to DARPA's approximately $3 billion; it is the size of a DARPA office. It now faces a challenge to its survival because the Trump administration, which has been proposing cuts to in alternative energy R&D, has proposed shutting it down, although Congress has continued to sustain it. Nonetheless, it represents an important innovation model that has had considerable success in its relatively short existence (ARPA-E, 2017).[17]

14 These technology challenges are detailed in, Bonvillian, "All that DARPA Can Be."

15 This section on ARPA-E draws from discussions with ARPA-E's directors, its deputy director for operations, and its program managers, including an extended session with four ARPA-E program managers on April 5, 2011, and from Bonvillian and VanAtta, "ARPA-E and DARPA." For disclosure, the author was involved in ARPA-E's founding, including testifying on the ARPA-E authorizing legislation (Bonvillian, 2007), writing about the concept (Bonvillian, 2006)., and working on ARPA-E organizational concepts for the Department of Energy Chief Financial Officer in February and March 2009.

16 H.R. 364 (2007), passed as part of the America COMPETES Act (2007).

17 See also, APRA-E (2017, 2018).

ARPA-E was formed by a director, Arun Majumdar, and staff fluent with the DARPA model and replicated the key elements in that model. Aside from the particular DARPA features, the discussion above focused on four overall roles that DARPA embodies as an innovation intermediary and change agent: its role as a critical innovation institution at earlier innovation stages, its linkage to implementation decision makers through the island-bridge model, its role in fostering a thinking community to enable and build on its innovations, and its ability to connect innovators with operators to enable implementation. Importantly ARPA-E performs these functions within its energy technology mission. But because ARPA-E's energy sector is different from DARPA's defense sector, it has had to adapt. DARPA has been able to leverage its position within DOD, a major technology procurement agency, to implement many of its innovations. In contrast, the Department of Energy (DOE) does not play a procurement role; ARPA-E's technologies must be implemented in the private sector, a massive legacy sector dominated by fossil fuel firms. This different implementation task required ARPA-E to add to the DARPA model, categorized into three broad areas below. While the description of DARPA, above, took a high-level view of its overall role in the innovation system, the description below of ARPA-E's somewhat different features tends to take a more ground-level approach.

1) *Sharpening the research visioning, selection, and support process.* Every strong innovation organization, from research groups, to start-ups and firms, to federal research agencies, must build a strong innovation culture. Organizational cultures in the innovation space tend to lock-in quite early in the organizational history, and, once set, patterns of interactions and performance become engrained into the entity's culture. ARPA-E's leaders had experience in a range of innovation organizational cultures, including DARPA, and worked to build their own innovation culture within ARPA-E. While it shares many features with DARPA, as noted above, it has its own new areas of emphasis.

ARPA-E's director and project directors (equivalent to DARPA's program managers) emphasize that they are working in what they call *the white space of technology opportunities*. Starting with their first research awards, they assert they have consciously attempted to fund higher risk projects that could be breakthroughs and transformational in energy areas where little work previously has been undertaken. This means that research awards are made seeking transformations, not incremental advance. Comparable to the DARPA model, this approach has placed *technology visioning* at the very front of the ARPA-E's research nurturing process.

ARPA-E has implemented an interesting *two-stage selection process*, offering applicants a chance to offer feedback to the initial round of reviews. This "second shot" and "feedback loop" in the review process have improved evaluations because the project directors know their conclusions will be critiqued, have helped educate project directors in new technology developments, and resulted in a number of reconsiderations of applications, improving the overall ARPA-E research portfolio.

The *empowered program manager culture*—Project directors form, with the director, macro challenges within the sectors they lead and retain a great deal of control over their research portfolios. They are "empowered" like DARPA project managers. Before a project director can select a technology project, he or she has to "sell" it to the director; the proposal often also has to survive rounds of brainstorming and vetting with project director colleagues. Project directors have to have what they refer to as "religion"—they have a vision of where they want to take their portfolios, performing as vision champions, to sell their projects both inside and outside ARPA-E. Part of "religion," then, is that they must work on being vision implementers. ARPA-E project directors have expressed the view that "religion" is the single most critical project manager quality, aside from technical excellence. To summarize, ARPA-E uses DARPA's "strong program manager" model for research award selections and calls on its program managers to exert zeal in advancing selected technologies through the implementation stage, and ARPA-E has pushed this model. ARPA-E has purposely not created a formal personnel evaluation process for its project directors—as with DARPA, project directors say they are expected to "manage to results", and they are judged by the director and their colleagues—peer pressure—based on the outcomes, impact, and results from the portfolios they select.

Portfolio approach—All ARPA-E projects are selected, as discussed above, to be game changers—to initiate energy breakthroughs. However, within that broad requirement, as project directors assemble their portfolios around a particular challenge area, project directors say they have found they need a "risk mix." They generally include some "out there" projects that may or may not materialize that are high risk, but the technology is so potentially important that it is well worth pursuing. But for most other portfolio technologies, the project directors want to see that they could be implementable in a reasonable period—that they could reach a cost range that would facilitate entry and commercialization. So there is a mix of portfolio balance between frontier and applied, science, and technology emphasis.

As with DARPA, ARPA-E project directors have adopted a *hands-on relationship with award recipients*, talking and meeting at frequent intervals to support their progress and help surmount barriers, and, when ready, to promote contacts with venture and commercial funding. In most research agencies, the job of the program manager focuses on the award selection process; in ARPA-E, this is only the beginning. Project directors view their jobs as technology enablers, helping their tech clients with implementation barriers.

2) *Building a community of support*. ARPA-E, a small R&D agency camped among much larger DOE R&D agencies, has needed collaborators to leverage its research on basic and applied sides. Therefore, it has worked from the outset on *building internal connections within DOE*. The Department's R&D is organized into basic and applied stovepipes, so ARPA-E found it could thus serve both sides by working to be a technology connector within DOE, particularly with the applied agencies. ARPA-E has also worked to include the major energy labs in its research consortia,[18] so the labs will view it as not simply a funding competitor but a funding supporter.

Summit—ARPA-E holds annual multi-day forums each spring to help its awardees build relations with venture capital (VC) firms and large and small energy and technology companies. These energy innovation summits have become one of the largest and most important energy technology showcase events in the nation, attracting large attendance and featuring prominent business, executive branch, and bipartisan Congressional leaders in speaking roles. VCs and energy companies annually swarm around ARPA-E technologies, building communication and goodwill among attendees, whatever their role. This has helped the growing field of energy technology highlight emerging technologies to potential private sector funders and has played a major role in putting ARPA-E on the map as an innovative agency. Importantly, the summits have helped in building an advanced energy technology *community* around ARPA-E.

Support community—ARPA-E has faced major funding challenges from the outset, which continue. As a result of the goodwill it built in its initial years, a community of support began to collect around ARPA-E to independently advocate for the agency's future, including VC firms, large and small firms that worked with ARPA-E, and universities, all enamored of its research model. Thus, a political support system is growing, separate and apart from ARPA-E (which cannot lobby under federal law) to back its efforts and continuation. ARPA-E has also received public support from some prominent business leaders. The continued growth of such a political support community could help assure ARPA-E's political future.

In summary, not only has ARPA-E proven a strong substantive success to date from a public policy perspective, a thinking community as well as a political support base has begun that could help sustain it over time.

3) *Technology implementation*. ARPA-E's director and project directors are acutely aware of their difficult task in launching technology into the complex, established legacy sector of energy. ARPA-E has therefore taken a number of steps to assist in taking its technology to implementation, commercialization, and deployment.

ARPA-E project directors *consider the implementation* process for technologies they are considering; before they fund a project, they evaluate the technology stand-up process and how that might evolve. Their focus is not simply on new technology, they seek to fund projects where they can see a plausible pathway to implementation. This is aided by the fact that ARPA-E project directors generally have both academic and commercial sector experience. On the commercial side, this experience ranges from work in VC firms and companies, to participating in technology-based start-up firms. This range of background in both academic and private sectors assists in understanding possible commercialization paths.

Tech to market team—In its most significant step toward moving its technologies toward implementation, ARPA-E has assembled a separate "Tech to Market" team working full-time to promote implementation and commercial advances for ARPA-E technologies. These team members work with particular project directors on the most promising technologies emerging from their portfolios. No other US R&D entity had formed such an explicit commercialization effort until ARPA-E. In effect, it has added a variation to DARPA's famous Heilmeier Catechism by requiring project directors and their Tech to Market team members to "tell me how your story will end then get there" (Heilmeier Catechism, 1975; Heilmeier, 1991). The tactics this team develops in implementing technologies can include creating follow-on approaches for ARPA-E-funded technologies through links with DOE-applied programs, connections to DOD test beds and procurement, and connections to VCs and interested company collaborators, or combinations of these. Their work includes identifying first markets and market niches for ARPA-E technologies. In

18 America COMPETES Act (2007), Sec. 904(e)(3) authorizes ARPA-E to fund "consortia. . ., which may include federally-funded research and development centers" (FFRDC's—including energy laboratories).

the ultimate compliment to ARPA-E, DARPA so liked the program that it hired ARPA-E's Tech to Market director to undertake the same job at DARPA.

Halo effect—ARPA-E consciously takes advantage of the "halo effect." Here, when ARPA-E selects a project for a research award, VCs and commercial firms are often willing to pick it up and move it toward commercialization. In other words, the private sector views the ARPA-E project selection process as rigorous and sound enough that it is prepared to fund projects emerging from that process.

Connecting to the industry stage-gate process—The stage-gate process, as noted above, is used by most major companies in some form in the management of their R&D and technology development (Cooper *et al.*, 2002). In this approach, candidate technology projects are reevaluated at each stage of development, weeded-out, and only the most promising from a commercial success perspective move to the next stage. This is not a process ARPA-E employs; like DARPA (as discussed above), it places technology visioning up front in its process and adopts a high-risk/high-reward approach to meet the technology vision. Recognizing that companies use the stage-gate approach, ARPA-E has worked with its researchers to get their technologies into a condition to survive it. For academic researchers in particular, this is not a familiar process. Because most early generation energy technologies are component technologies and will have to fit into existing systems and platforms controlled by existing companies (Weiss and Bonvillian, 2009: 185–190), ARPA-E project directors are recognizing that many of the technologies it nurtures must slot into the stage-gate industry practice if they are going to link with industry. So preparing its technologies (and technologists) to withstand this process has become a significant step toward commercialization.

New energy technologies can take two decades to scale, and ARPA-E is only 7 years old. However, ARPA-E reported in 2017 that since 2009, it provided approximately $1.3 billion through 30 focused programs and three open-funding solicitations to some 475 projects (ARPA-E, 2017: 1). Of those, 206 were now "alumni" projects; the rest were ongoing. ARPA-E's project teams cumulatively published 1104 peer-reviewed technical papers that have been cited 13,518 times and were awarded 101 patents. Many teams successfully leveraged ARPA-E's investment: 36 started new companies, 60 continued their technology development with other government support, and 45 have cumulatively raised $1.25 billion in publicly reported funding from the private sector to bring their technologies into commercial applications. These statistics are strong success metrics.

To summarize, ARPA-E has not only worked to replicate elements at DARPA but also attempted to build new elements in its innovation ruleset as it confronts unique features of the legacy energy sector where its technologies must land, and of the DOE bureaucracy it must work with. These new elements can be grouped into three broad areas, as detailed above: in sharpening the research visioning, selection, and support process; in building a politically survivable support community; and in the implementing and deployment process for its technology advances. Organizational tools in these categories developed at ARPA-E present lessons that are relevant to other innovation intermediaries.

6. The IARPA model

IARPA's first director, Lisa Porter, named in 2008, was a former DARPA program manager who understood and consciously attempted to replicate DARPA's strengths and "high-risk, high reward" approach. Both IARPA and DARPA hire term-limited program managers with outstanding scientific and engineering credentials and experience.[19] Like DARPA, IARPA competitively selects new projects for funding using the Heilmeier Questions. Like DARPA, IARPA has no lab and conducts no research itself, competitively awarding research contracts and grants to leading teams of academic and industry researchers, using strong program managers without peer review systems. Also like DARPA, programs have clear goals and definite ends. Program teams are regularly evaluated and teams are often cut before a program ends, depending on progress. There also are significant differences. While DARPA supports defense missions, IARPA supports national intelligence missions, which can involve quite different technologies. Five of IARPA's key organizational mechanisms to promote its innovation role are discussed below.

1) *Technology implementation-tournaments and testing*. According to its director from 2014–2018, Jason Matheny, many of IARPA's programs are organized as tournaments in which multiple teams are funded in parallel to pursue the same technical goals, scored on a common set of metrics. This competitive approach has tended to produce a range of possible solutions and pathways. As a result, IARPA spends a large percentage of its budget

19 Much of the IARPA material below is from a communication from Jason Matheny, IARPA Director, July 11, 2017.

(approximately 25%) on independent testing and evaluation. This testing stage plays such a central role at IARPA that it has a Chief of Testing and Evaluation, with contractor support, to ensure that these tests follow best practices in experimental design and statistical inference. The tournament approach and strong emphasis on testing constitute a different approach to technology implementation from DARPA and ARPA-E.

2) *Empowered program managers*. The strong program manager role is comparable to DARPA's. IARPA has some 25 program managers compared to approximately 100 at DARPA and 15 at ARPA-E. Program managers must nurture and pitch their proposed programs, and the director and deputy director then move quickly to approve such new programs for funding. Program managers have broad independence to manage their programs within their approved budgets. They write the solicitations for proposals, they lead proposal reviews, and they make the decisions regarding program direction and evaluation. Every six months, each program is reviewed by the IARPA senior staff, by outside technical reviewers, and by transition partners, to reevaluate whether continued funding is justified for all research teams and for the program as a whole. Typically, at least one team is cut per program phase. In some cases, programs are discontinued. As with DARPA and ARPA-E, IARPA program managers have a hands-on relationship with their research teams. Program managers have conference calls every two weeks with each team, review monthly written reports from each team, and have in-person meetings with each team every quarter, on-site visits, and PI meetings.

According to its director, IARPA has funded research at over 500 organizations in over a dozen countries (Matheny, 2017). About one-third of IARPA's funding goes to universities and colleges, about one-third to small firms, about one-sixth to large firms, and about one-sixth to Federally-Funded Research and Development Centers (FFRDCs) and Government labs. So its program managers have a full range of innovation actors to select from. The bulk of its R&D funding goes to research in computing, machine learning, human judgment, sensors, and intelligence IT platforms.[20]

DARPA and ARPA-E pride themselves on their ability to hire their program managers quickly, outside of traditional civil service hiring procedures, which helps them move fast on technology challenges. IARPA, however, faces a major challenge because of its lengthy time line for hiring program managers. This is because its program managers must obtain a high-level security clearance before beginning work. This takes several months, and in some cases, can take more than a year.

3) *Ensuring buy-in from agency customers*. This intelligence technology focus results in organizational changes compared to DARPA, just as ARPA-E's energy focus required changes. IARPA's research tends to focus on key intelligence problems that have limited commercial markets. For example, programs in quantum computing and superconducting computing have few near-term commercial applications. Its work in natural language processing focuses on languages of little commercial interest. As a result, it has few commercial off-ramps for its research and focuses on technology transition directly to intelligence agencies. Thus, while DARPA stood up its computing initiatives in the private sector, and ARPA-E must stand up its energy initiatives in the private sector, IARPA must focus exclusively on government intelligence agencies as customers for its technologies. While this can mean a more assured route to technology implementation, intelligence is also a long-established bureaucratic sector with legacy features.

There are spillover opportunities over time for the private sector, however, because it has relatively open research processes. Most of IARPA's research is unclassified. IARPA's research is largely open to university researchers and to foreign participation, and it has no publication restrictions and is published in peer-reviewed journals.

IARPA's agency-focused transition does face technology implementation challenges. A total of 70% of IARPA programs beyond their midpoint, according to its director, have achieved at least one technology transition to an intelligence agency (Matheny, 2017). However, the intelligence community lacks DOD's large industrial base and constellation of labs, so IARPA has to make special efforts to support technology transition directly with intelligence agencies. In particular, it has a full-time Chief of Technology Transition with contractor support to work with these potential government customers. This group is analogous to DARPA's tech to market team.

IARPA works directly with the intelligence community to get its technologies implemented. It involves it agency transition partners in the program pitch, in proposal reviews, and in program reviews. Technology transition plans with the interested agency are typically developed during the second or third year of a program. The Chief of Technology Transition directly supports these efforts. IARPA's strong testing and evaluation emphasis also helps enable agency transitions, since technologies they may be considering have been subject to, in effect, a validation

20 See IARPA (2018.

process. There are significant lessons from these steps to integrate technology development with customer agencies. These conscious transition efforts mark IARPA as a different kind of R&D entity, using the extended pipeline model.

4) *Multigenerational technology development*. Both DARPA and ARPA-E have faced challenges when they undertake multigenerational technology development. In other words, with term-limited program managers, once a program manager nurtures an area how is it sustained after he or she departs, and then built on and moved to the next related set of advances? IARPA has to deal with this problem as well. IARPA program managers often recruit their replacements. Contract employees at IARPA who support the program managers often serve as the institutional memory across multiple program managers. In a number of cases, one program may be organized to lay the groundwork for the next. For example, IARPA's work in quantum computing has been organized along a set of sequential technical milestones, which can move from one program manager to the next.

5) *Cross-disciplinary thinking communities*. Like DARPA and ARPA-E, IARPA has worked to build a "thinking community" around its research focus areas but has added an interesting element. Most IARPA programs require the formation of research teams that cross disciplines. In some cases, these research communities have not previously interacted. For example, according to its director, IARPA's work on the social science of cybersecurity has brought together sociologists and cybersecurity experts, and its work in geopolitical forecasting has brought together political scientists and computer scientists. This multidisciplinary thought community, particularly across social and physical sciences, is an interesting IARPA feature.

Because its technologies serve intelligence needs, it is hard to evaluate IARPA's success metrics. However, IARPA-supported quantum computing research was named a *Science* magazine Breakthrough of the Year in 2010 (Ford, 2010). In 2015, IARPA was named to lead foundational R&D in the interagency National Strategic Computing Initiative, in 2014, it was made part of the interagency BRAIN Initiative, and in 2016, it was made part of Nanotechnology-Inspired Grand Challenge for Future Computing.[21] These are all external signals of strong technical capability, in addition to its 70% rate of transitioning technologies into agencies.[22]

To summarize, IARPA, in addition to replicating the core of the DARPA model, brings interesting variations as well. Its "tournament" approach to many of its projects, where multiple teams are funded in parallel to pursue the same technical goals, provides an interesting competitive approach to produce a range of possible solutions and pathways. It spends a large percentage of its budget on independent testing and evaluation under a Chief of Testing and Evaluation. This testing regime has tended to validate its technologies and make them more acceptable to its intelligence agency customers. It involves its agency transition partners in the research program pitch, in proposal reviews, and in program reviews, which has produced further customer buy-in, smoothing the path to technology implementation. In addition, its multidisciplinary approach to building a "thinking community" to contribute to its technology capabilities, particularly across social and physical sciences, is an interesting IARPA feature. All are variations from the basic DARPA model that merit consideration.

7. Two challenges to the DARPA model—manufacturing and scaling up start-ups

DARPA and its clones often innovate in the areas of "hard" technologies that must be manufactured, in addition to work in software. They also rely on innovative, entrepreneurial start-ups to bring their hard technology projects into implementation. Both systems are under challenge which could affect the effectiveness of the DARPA, ARPA-E, and IARPA models.

Although there is a substantial argument that manufacturing, particularly initial production of new technologies and complex, high-value products, is a significant stage of the innovation system as Suzanne Berger has articulated (Berger and MIT Task Force on Production and Innovation, 2013), US innovation agencies historically have not organized around it. However, as noted above, other nations have developed what can be termed "manufacturing led" innovation systems, which is the dominant model in Germany, Japan, Korea, and now China (Bonvillian and Weiss, 2015: 184–186).[23] Emblematic of "manufacturing-led" is Japan's quality manufacturing revolution of the 1970s–1980s (Womack *et al.*, 1990),[24] Germany's system of industrial support through its Fraunhofer institutes and

21 See White House, 2014, 2015; Whitman *et al.* 2015.

22 See IARPA (2016, 2017).

23 See also, discussion of China in, Bonvillian and Singer (2018).

24 See also, discussion of Japan in Bonvillian and Singer (2018: 37–44.

apprenticeship programs (Bonvillian and Singer, 2018: 178–183), and lately, China's rapid prototyping and scale-up capacity (Nahm and Steinfeld, 2013: 288–300).

The United States missed this model. In the immediate postwar period when it was forming most of its R&D agencies, the United States had the strongest manufacturing sector in the world, operating at a level of mass production efficiency that no other economies were close to. There was no reason to bring innovation models to production (Bonvillian and Singer, 2018: 34, 35). Both civilian and military innovation models—pipeline and extended pipeline—focused on broader technology development, not on technologies and processes for manufacturing innovation. The United States therefore missed manufacturing-led innovation and then paid a significant price in the decline of its manufacturing base in the early 2000s. The one-third manufacturing job decline from 2000 to 2010 turned out to be symptomatic of a decline in production capability. Widespread offshoring of manufacturing, encouraged by generations of MBAs and a financial sector taught to focus firms on "core competencies" and to go "asset light," was also a critical factor in limiting domestic production capacity (Berger, 2014; Bonvillian and Singer, 2018: 117, 118). Linda Weiss has noted the problematic future of American economic primacy and national security, as its financialized corporations curtailed investment in manufacturing and related innovation (Weiss, 2014: 203–209). Production, particularly initial production of new technologies, can be highly innovative, involving creative engineering, design, technology advances, and production processes. For the DARPA model agencies to be cut off from these innovation system capabilities, and unable to rely on a strong US manufacturing base for rapid prototyping and innovative production, spells a major potential challenge to their ability to develop and implement hard technologies. Although the United States is now pursuing an "advanced manufacturing" model through an innovative group of 14 new advanced manufacturing institutes (Bonvillian and Singer, 2018: 131–186), this effort is still in early stages, and it is not clear it will have the political support to be sustained over the extended period required.

The second challenge is that US VC has largely withdrawn from support of start-up firms with hard technologies that must be manufactured. Bonvillian and Singer (2018: 187–215)[25] VC firms are focused on software, biotech, and services start-ups where they can more readily manage the scale-up process and timetable. Hard technologies typically require more time, risk, and capital for scale-up so increasingly fall outside the VC model. Since VCs dominate the scale-up process for its small, innovative companies, the United States is increasingly leaving hard technologies by the technology wayside. Because they leverage the private sector for implementation, this will affect the ability, in particular, of DARPA and ARPA-E to use the entrepreneurial approach they have relied on for scaling up their hard technologies. A new approach, termed "innovation orchards," is now evolving to fill this gap which entails creating shared technology, equipment, and know-how-rich spaces for scaling up start-ups through advanced prototype, production design, and pilot production (Singer and Bonvillian, 2017). In effect this approach attempts to substitute space for capital. However, it is likewise at a very early stage. In the meantime, this creates a serious implementation challenge for the DARPA model.

8. Conclusion

DARPA, ARPA-E, and IARPA share an ambitious innovation organization model, operating as public sector intermediaries that pursue high-risk/high-reward, breakthrough research. Importantly, they also actively promote its implementation. They are therefore much more activist than the standard American R&D mission agency, performing as change agents within the often conservative "legacy" sectors they operate within. The chapter examined the DARPA model and its variations in ARPA-E and IARPA in detail. It placed these agencies it in the context of the overall US innovation system—DARPA and IARPA are leading examples of the "extended pipeline" model, while ARPA-E is located within a "pipeline" model agency, trying to reach further down the innovation pipeline. All face the types of innovation barriers common to legacy sectors, which further challenge their efforts to implement their innovations. Despite these challenges, the DARPA model has proven quite dynamic; DARPA has an unparalleled record of technological advance, and the other two are rapidly building their own records. ARPA-E and IARPA show that the DARPA model is now a proven one in the innovation space, clearly relevant to other technology sectors. Therefore, the specifics of their innovation organization present important innovation options deserving close examination, as attempted here. However, because all three agencies work in significant part on "hard" technologies that must be manufactured, they face two significant new structural challenges in the US innovation system: in

25 These developments are reviewed in further detail in, Singer and Bonvillian (2017).

manufacturing and start-up scaling. Their ability to achieve innovation implementation in the future in hard technology fields may depend on progress in addressing these two new innovation system challenges.

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