The DARPA Model for Transformative Technologies

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

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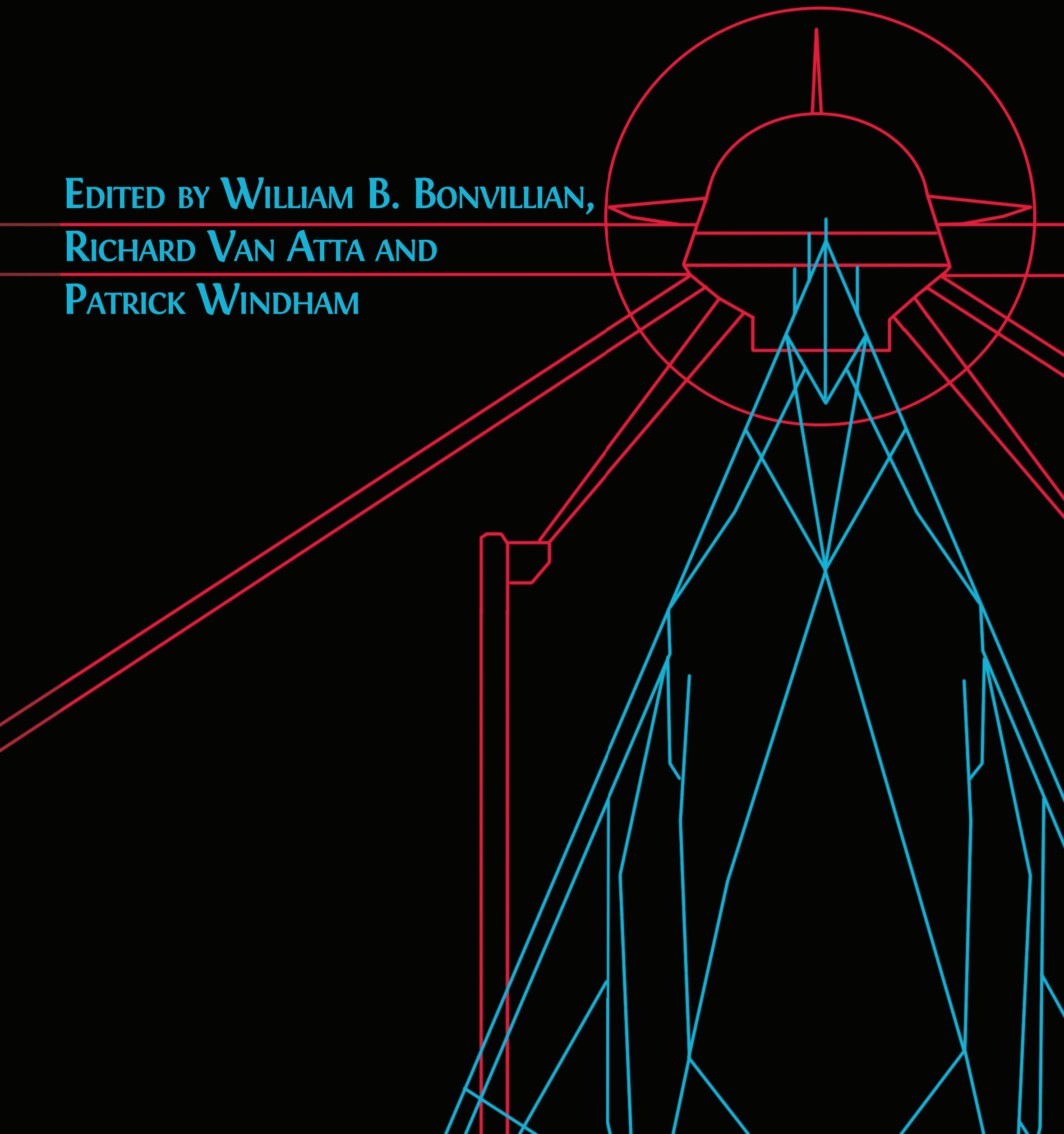

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14. IARPA

A Modified DARPA Innovation Model[1]

William B. Bonvillian

The DARPA model for organizing innovation has now been copied in other U.S. agencies. This is in part because DARPA is famous for playing critical roles in the information technology (IT) revolution—from support for personal computing to the Internet, as well as in stealth and drones. As discussed across this volume, DARPA 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 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, and is discussed in Chapter 13. The Intelligence Advance Research Projects Agency (IARPA), reviewed here, began operating in 2007, bringing a DARPA model

1 This paper contains material that originally appeared in 2018 as "DARPA and its ARPA-E and IARPA clones: a unique innovation organization model", *Industrial and Corporate Change* 27/5: 897–914, https://doi.org/10.1093/icc/dty026, https://academic.oup.com/icc/article-abstract/27/5/897/5096003

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to development of intelligence-related technologies. A third DARPA clone, the Homeland Security Advanced Research Projects Agency (HSARPA) was authorized in 2002 as a DARPA-like entity in the then newly-formed Department of Homeland Security. However, it was not adequately established at the time, and much of its early staff, many of whom came from DARPA, left in frustration. It was not allowed to be a separate operating unit within the department's science and technology directorate, subsumed within a more traditional budget and policy office. The Department's Undersecretary for Science and Technology from 2009–2013 worked to reestablish HSARPA during the Obama Administration, however, the Trump Administration has since moved away from it. Because of these operational problems, this chapter does not attempt to evaluate it.

Concerning IARPA, like DARPA, it operates as public sector intermediary, pursuing breakthrough research but also actively promoting its implementation. Like DARPA, it is therefore much more activist than the standard American R&D mission agency, acting as a change agent within the often conservative "legacy" sectors it serves. This chapter examines IARPA in more detail, comparing it to DARPA, and concludes by noting two structural challenges in their innovation systems that DARPA, ARPA-E and IARPA all face.

The DARPA Model in the Context of Innovation Policy

DARPA was a Cold War creation, formed in direct response to a technological crisis. 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 sixty years later—that innovation theory is catching up, and consideration is being given to where an agency like DARPA might fit within this theory.

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 U.S. 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.[2] Paul Romer and other New Growth Theorists argued the importance of technological learning as the underpinning for Solow's technological advance theory.[3] 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 in understanding comparative innovation systems of assessing the actors in an innovation system and their comparative strengths.[4] We can enlarge this concept to constitute a third direct 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 U.S. 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 U.S. R&D agencies 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.[5] Lewis Branscomb and Phillip Auerswald

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2 Solow, R. M. (2000). *Growth Theory, An Exposition*. 2nd ed. Oxford: Oxford University Press, http://nobelprize.org/nobel_prizes/economics/laureates/1987/solow-lecture.html.

3 Romer, P. (1990). "Endogenous Technological Change", *Journal of Political Economy* 98/5: 72–102, http://pages.stern.nyu.edu/~promer/Endogenous.pdf

4 Nelson, R., ed. (1993). *National Systems of Innovation*. New York, NY: Oxford University Press, 3–21, 505–23. This "innovation organization" factor is also elaborated on at length in Bonvillian, W., and Weiss, C. (2015). *Technological Innovation in Legacy Sectors*. New York, NY: Oxford University Press, 25–27, 181–86, 190–92, https://doi.org/10.1093/acprof:oso/9780199374519.001.0001

5 Stokes, D. E. (1997). *Pasteur's Quadrant, Basic Science and Technological Innovation*. Washington, DC: Brookings Institution Press.

articulated the "valley of death" critique: the disconnect in the U.S. system between research and later stage development led to system failures in commercialization of research results.[6] This concern has been the major focus of U.S. science and technology policy literature for the past twenty years, with resulting discussions of bridging solutions across this valley. Of course, the pipeline model is not the only U.S. innovation system model.

As detailed in Chapter 12 of this work, there are five fundamentally different innovation approaches that help us sort out the roles of DARPA and its clones. These drive the dynamics of innovation in different settings: the innovation pipeline, induced innovation, the extended pipeline, manufacturing-led innovation, and innovation organization.[7] These provide a framework for understanding the place in the innovation system occupied by DARPA and IARPA, as well as ARPA-E. 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 U.S. 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. However, most technology comes from private sector firms that respond to market opportunities. This constitutes a second model, "induced innovation". Vernon Ruttan is the growth economist who discussed this as the dominant way industry innovates, by identifying market opportunities then innovating to fill them.[8]

6 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, https://www.nist.gov/sites/default/files/documents/2017/05/09/gcr02-841.pdf

7 These models are discussed at length in, Bonvillian and Weiss. (2015). *Technological Innovation*, 23–30, 181–76, which is drawn from here.

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

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. The third model can be termed the "extended pipeline", where certain U.S. R&D organizations, particularly through the Defense Department (DOD), and including DARPA, 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 pipeline.[9] This means support not just for front end research and development (R&D) but also for each successive "back-end" stage, from advanced prototype to demonstration, testbed, and often to initial market creation, where DOD will buy the first products.[10] 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.[11] The extended pipeline facilitates the bridging of the "valley of death" between advanced research and implemented technology. In general, U.S. innovation models in recent decades have tended to stretch their capabilities further down this innovation pipeline.[12]

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.[13] This is augmented by applied research

9 Bonvillian and Weiss. (2015). *Technological Innovation*, 181–86.

10 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 469, https://doi.org/10.1007/s10961-011-9223-x, https://link.springer.com/article/10.1007%2Fs10961-011-9223-x

11 Although he did not use the term "extended pipeline", Vernon Ruttan wrote about the Defense role in evolving these technologies, Ruttan, V. W. (2006). *Is War Necessary for Economic Growth? Military Procurement and Technology Development*. New York, NY: Oxford University Press.

12 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

13 Bonvillian and Weiss. (2015). *Technological Innovation*, 25, 181–85.

and development that is integrated with the production process. It is typically industry-led, but with strong governmental industrial support. While countries like Germany, 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 its clones to translate their technologies into actual innovation.

The fifth model, "innovation organization", is different from the others.[14] 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. 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.

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 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.[15]

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

14 Bonvillian and Weiss. (2015). *Technological Innovation*, 25–27, 186.

15 Shapira, P., and Youtie, J. (2016). *The Next Production Revolution and Institutions for Technology Diffusion*. Presentation at the Conference on Smart Industry: Enabling the Next Production Revolution, OECD and Sweden Ministry of Enterprise and Innovation, Stockholm, 18 September.

the breakthrough to technology implementation. As intermediaries, they also operate as change agents.

DARPA and IARPA are clearly mainstays of the extended pipeline model, able to apply acquisition budgets from their overall agencies to implement technologies they research. Therefore, they are reaching toward the unifying "innovation organization" model. This makes them quite different from other R&D agencies. Nonetheless, it is also important to note that DARPA and later IARPA are able to succeed because the U.S. already had a very rich and complex publicly funded science and technology system, including the federal labs, university-based labs, the National Science Foundation, as well at an earlier time a network of quite significant private sector labs, including, of course, Bell Labs.[16] DARPA and later IARPA 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.

However, 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.

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-payoff" approach. Both IARPA and DARPA hire term-limited program managers with

16 Gertner, J. (2012). *The Idea Factory, Bell Labs and the Great Age of American Innovation*. Penguin Publishing Group: New York, N.Y.

outstanding scientific and engineering credentials and experience.[17] Like DARPA, IARPA competitively selects new projects for funding using "The Heilmeier Catechism"—a set of questions to guide program selection.[18] 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. 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. Some of IARPA's key organizational mechanisms to promote its innovation role are discussed below.

1) *Technology Implementation—Tournaments and Testing.* According to its current director, 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 (approximately 25 percent) 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 twenty-five program managers compared to approximately one hundred at DARPA and fifteen at ARPA-E. Program managers must nurture and pitch their proposed programs and the director

17 Much of the IARPA material below is from Jason Matheny, IARPA director, Personal Communication, 11 July 2017.

18 Chapters 1, 8, and 10 in this volume provide more details about "The Heilmeier Catechism".

> 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 re-evaluate 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, they review monthly written reports from each team, and have in-person meetings with each team every quarter, at on-site visits and PI Meetings.

According to its director, IARPA has funded research at over 500 organizations in over a dozen countries. 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 FFRDCs and Government labs. In this way, 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 information technology platforms.[19]

DARPA and ARPA-E have prided 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 timeline 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

19 For a summary of current agency work, see IARPA. "Research Program, Current Research", https://www.iarpa.gov/index.php/research-programs

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

IARPA's agency-focused transition does face technology implementation challenges. Seventy percent of IARPA programs beyond their midpoint, according to its director, have achieved at least one technology transition to an intelligence agency. 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 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, 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. However, IARPA has also worked to add 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.[20] In 2015, IARPA was named to lead foundational research and development 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 percent 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 it 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.

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20 Ford, M. (2010), "Science's Breakthrough of 2010: A Visible Quantum Device", *Ars Technica*, 23 December, https://arstechnica.com/science/2010/12/sciences-breakthrough-of-2010-a-macro-scale-quantum-device/

21 See White House. (2015). "Executive Order: Creating a National Strategic Computing Initiative", July 29; White House. (2014). "Fact Sheet: Over $300m in Support of the BRAIN Initiative", 30 September, 5.; Whitman, L., Bryant, R., and Kalil, T. (2015)., "A Nanotechnology-Inspired Grand Challenge for Future Computing", White House, 30 October.

22 For a useful summary of IARPA's technology progress, see IARPA. (2018). *2018 Year in Review*. Washington DC: IARPA https://www.iarpa.gov/index.php/about-iarpa/2018-year-in-review?highlight=WyJ5ZWFyIiwieWVhcidzIiwiaW4iLCJyZXZpZXciLCJ5ZWFyIGluIiwieWVhciBpbiByZXZpZXciLCJpbiByZXZpZXciXQ==; and IARPA. (2016). *2016 Year in Review.* Washington DC: IARPA, https://www.iarpa.gov/index.php/228-about-iarpa/2016-year-in-review/889-2016-year-in-review?highlight=WyJ5ZWFyIiwieWVhcidzIiwiaW4iLCJyZXZpZXciLCJ5ZWFyIGluIiwieWVhciBpbiByZXZpZXciLCJpbiByZXZpZXciXQ==

Two Challenges to DARPA and its Clones—Manufacturing and Scaling up Startups

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 startups to bring their hard technology projects into implementation. Both systems are under challenge, and this 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,[23] U.S. innovation agencies historically have not organized around it. However, as noted in Chapter 12, other nations have developed what can be termed "manufacturing-led" innovation systems, which is the dominant model in Germany, Japan, Korea, and now China.[24] Emblematic of "manufacturing-led" is Japan's quality manufacturing revolution of the 1970s-80s,[25] Germany's system of industrial support through its Fraunhofer institutes and apprenticeship programs,[26] and lately, China's rapid prototyping and scale-up capacity.[27]

The U.S. missed this model. In the immediate postwar period when it was forming most of its R&D agencies, the U.S. 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.[28] Both civilian

23 Berger, S., with the MIT Task Force on Production and Innovation. (2013). *Making in America*. Cambridge, MA: The MIT Press.

24 Bonvillian and Weiss. (2015). *Technological Innovation*, 184–86. See also the discussion of China in, Bonvillian, W. B., and Singer, P. (2018). *Advanced Manufacturing—The New American Innovation Policies*. Cambridge, MA: The MIT Press, 8, 45–52, https://doi.org/10.7551/mitpress/9780262037037.001.0001

25 Womack, J. P, Jones, D. T., and Roos, D. (1991). *The Machine that Changed the World: The Story of Lean Production*. New York, NY: Harper Perennial. See also, discussion of Japan in Bonvillian and Singer. (2018). *Advanced Manufacturing*, 37–44.

26 Bonvillian and Singer. (2018). *Advanced Manufacturing*, 178–83.

27 Nahm, J., and Steinfeld, E. (2013). "Scale-Up Nation: China's Specialization in Innovative Manufacturing", *World Development* 54: 288–300, https://doi.org/10.1016/j.worlddev.2013.09.003

28 Bonvillian and Singer. (2018). *Advanced Manufacturing*, 34–35.

and military innovation models—pipeline and extended pipeline—focused on broader technology development, not on technologies and processes for manufacturing innovation. The U.S. therefore missed manufacturing-led innovation, and subsequently paid a significant price in the decline of its manufacturing base in the early 2000s. The one-third manufacturing job decline from 2000–2010 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.[29] 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.[30] 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 U.S. manufacturing base for rapid prototyping and innovative production, spells a major potential challenge to their ability to develop and implement hard technologies. Although the U.S. is now pursuing an "advanced manufacturing" model through an innovative group of fourteen new advanced manufacturing institutes,[31] 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 U.S. venture capital (VC) has largely withdrawn from support of startup firms with hard technologies that must be manufactured.[32] VC firms are focused on software, biotech and services startups where they can more readily manage the scale-up process and timetable. Hard technologies typically require more time, risk

29 Berger, S. (2014). "How Finance Gutted Manufacturing", *Boston Review*, 1 April, http://bostonreview.net/forum/suzanne-berger-how-finance-gutted-manufacturing; and Bonvillian and Singer. (2018). *Advanced Manufacturing*, 117–18.

30 Weiss, L. (2014). *America Inc.? Innovation and Enterprise in the National Security State*. Ithaca, NY: Cornell University Press, 203–09.

31 Bonvillian and Singer. (2018). *Advanced Manufacturing*, 135–86.

32 Bonvillian and Singer. (2018). *Advanced Manufacturing*,187–215. These developments are reviewed in further detail in, Singer, P., and Bonvillian, W. B. (2017). "Innovation Orchards: Helping Startups Scale", *Information Technology and Innovation Foundation*, Washington, DC, http://www2.itif.org/2017-innovation-orchards.pdf

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 U.S. 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. This entails creating shared technology, equipment and know-how rich spaces for scaling-up startups through advanced prototype, production design and pilot production. 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.

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 has summarized the DARPA model and reviewed its variations in IARPA in detail. It placed these agencies it in the context of the overall U.S. 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 U.S. innovation system: in manufacturing and startup 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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