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The new model innovation agencies: An overview

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There have been four major innovation organization policy moments for the US federal government driven by the demands of politics and technology since World War II: first, the immediate post-war period where the Cold War helped drive a basic research model for new and expanded science agencies; second, the Sputnik aftermath with the formation of the Defense Advanced Research Projects Agency and scaled up funding for science; third, the competitiveness era 'valley of death' programs of the 1980s, and finally, a recent energy technology shift driven by energy and climate demands. Some are advocating a fifth: advanced manufacturing. In that lengthy evolution, what lessons have we learned about the design of federal innovation organizations? What are the institutional elements in the 'new generation' innovation policy programs now developing or under consideration? The focus is on the evolving federal agency role: what innovation stages is it organized around within the innovation pipeline and how does it link to other innovation actors?

Keywords: connected science; technology challenge model; innovation ecosystem.

1. The post-war disconnected science model

The federal innovation role shifted from modest[1] to major during World War II. Vannevar Bush, President Franklin Roosevelt's wartime science czar, led a highly connected system of innovation actors,[2] closely linking industry, government and university research. Then, after the war he dismantled this system and substituted an alternative one.[3]

As Roosevelt's agent, Bush shaped most defense research efforts under two flexible wartime committees, setting up relatively flat, non-bureaucratic, interdisciplinary project teams oriented to major technology challenges, such as for radar at the Rad Lab and atomic weapons at Los Alamos, as implementing task forces. These innovation institutions were placed into the hands of a remarkable series of scientist-administrators, including Alfred L. Loomis (Conant 2002), J. Robert Oppenheimer (Bird and Sherwin 2005), and Lee A. Dubridge (Greenstein 1997). Bush and his colleagues created what we can call a 'connected science' approach, where technology breakthroughs at the science stage were closely connected to the follow-on applied stages of government-supported development, prototyping, test beds and production, operating under what can be called a 'technology challenge' model. Not only were the stages of research linked, but the innovation actors were also linked. Government supported all the R&D stages, as well as the implementation stages, encouraging close connections between government, university and industry innovation actors.

When the war ended and the military was being dismantled in the expectation of world peace, Bush was able to salvage a residual level of federal science investment. In his 1945 polemic for science support, *Science the Endless Frontier* (see also Zachary 1999; Mazuzan 1994; Blanpied 1998). Bush argued that the US government should fund basic research, which would deliver ongoing progress to the country in economic growth, national security and health. In other words, he proposed ending his wartime model of connected science R&D, organized around major technology challenges, in favor of making the federal role one of funding only one stage of technology advance: exploratory basic research.[4] Bush's approach became known as the 'pipeline' model for science investment.[5] The federal government would load basic science into one end of an innovation pipeline hoping that industry would pick up the early- and late-stage technology development and prototyping roles inside the pipeline, with new technology products emerging from industry at the end.

While Bush proposed to achieve research coherence under a single organization—the National Science Foundation (NSF)—authorization of NSF was delayed, and in the interim science agencies multiplied.[6] Bush's pipeline concept of federal funding focused on basic science prevailed, but his more centralized science support model did not. The result was a new generation of highly decentralized science agencies, each generally adopting his pipeline model for the federal science role.

These two developments left US science fragmented at the institutional level: overall science organization was split among numerous science agencies, and federal investment was primarily focused on only one stage of the technological pipeline—basic research.[7] Bush thus left a legacy of two conflicting models for scientific organizational advance: the connected, challenge model of his World War II institutions, and the basic science-focused, disconnected, multi-headed model of post-war US science institutional organization.

Why did Bush create the disconnect, especially since he understood well the virtues in a connected innovation system he had created (Zachary 1999)? First and foremost, he was offering his proposal at a time when federal funding was about to go into steep decline at the end of World War II, and he was probably trying to hang onto a foundational part of the system he had created during the war: university research. Basic research also had the virtue of being the least costly innovation stage: research is relatively cheap compared to the scale-up needed for later stages. Second, he had seen and was probably wary of the way science had entered into the US political system during the war, and wanted to put some distance between science and the threat of political interference (Bush 1970). Third, as a friend of Oppenheimer with his own ties to the physics community, he was aware of that community's post-Hiroshima questions about deeply tying science to warfare. While remaining sympathetic to the scientific needs of war, he may also have wanted to create some additional space for science.[8] Finally, the whole country, including Bush, had seen basic science move rapidly from theory to practice in the Manhattan Project, so there was broad support for the basic research investment he was advocating.[9] Bush's decision was probably primarily driven by budget realism and the need to hold onto the federal research university model he had created during the war, but he also held some additional, deeper concerns about the direction of science and its control by government.

Bush's model was a political success, subsequently building on Cold War concerns over US leadership in science. NSF, the Department of Energy (DOE) Office of Science, and the National Institutes of Health (NIH) all continue to follow his approach. The network of federal basic research agencies enabled federally-funded US research universities, which became the leading universities in the world. It was a dynamic model with research grant agencies with a range of missions linked to university recipients competing for grant awards for basic research. But this system was disconnected from the later stages of innovation.

2. The Sputnik challenge of 1957 and rise of the Defense Advanced Research Projects Agency model

While the civilian research agencies moved into a disconnected model, the defense agencies by 1949 found themselves in a Cold War. They could not live with the inherent inefficiency of a disconnected model, so began by the end of the 1940s to recreate the 'connected' science and technology model that had served them well in World War II. The famous early computer technology programs for air defense, Whirlwind and SAGE, were iconic examples of this return to a connected effort (Hughes 2000; Redmond and Smith 2000).

A crisis in confidence over US science leadership was created by the Soviet launch of Sputnik in 1957. These anxieties over geopolitical developments created a political driver for science support, bringing new institutions and investments. US government R&D investment as a percentage of gross domestic product reached a post-war height in the mid-1960s: 2% by 1964 compared to less than 1% today (National Science Foundation 2012). Two major new agencies, the Defense Advanced Research Projects Agency (DARPA) then the National Aeronautics and Space Administration (NASA) were created to meet the Sputnik challenge. Both broke out of the basic research mode, although we focus on DARPA here.

Created in 1958 by Eisenhower as a unifying force for defense R&D in light of the stove-piped military services' space programs that had helped lead to the USA's Sputnik failure, DARPA became a unique entity. DARPA was set up to address deficiencies in R&D collaboration between the military services, rather than as a counterpoint to civilian agencies, but it is the true successor of Bush's Office of Scientific Research and Development, not the NSF. It was a particularly interesting model, very different from the Vannevar Bush basic research agency. DARPA's aim was a 'right–left' translational approach—decide the technologies you require from the right side of the innovation pipeline, then nurture breakthrough science advances on the left side of the pipeline to achieve that goal.[10] DARPA embodied a return to Bush's earlier World War II 'connected science' through a technology 'challenge' model. DARPA, the most successful of the post-war and Cold War science and technology agencies, led the information technology (IT) revolution (Waldrop 2001: Chapters 2, 5–7, 466–71) and a long series of other major advances (Ruttan 2006: 91–129; Van Atta 2008; Van Atta et al. 2003). DARPA, as it came into its own in the 1970s and 1980s, was a counterweight to the swing toward the 'pure' basic research approach. While DARPA illustrates the connected science approach, there are also political design lessons to be drawn from this connected model.

DARPA operated not only in the basic research space but further down the innovation pipeline in the development and prototyping spaces and often was able to hand on its technology advances to military procurement for initial product implementation. In the ideological parlance of the time, it was 'picking technology winners and losers'. Yet it defused this debate by tying its intervention in later stage development to the necessities of its national security mission. It offered a pragmatic solution—the value of technology advance for the national security overrode ideological concerns about the appropriate role of the federal government in the marketplace.[11] In other words, it showed that an agency operating in the science–technology development continuum can be tethered to a mission recognized as politically significant to avoid ideological differences.

Despite being tied to a security mission, DARPA (and the Department of Defense (DOD)) played a keystone role in the 1990s IT innovation wave and the accompanying resurgence of the US economy. DARPA deliberately passed its contributions to the IT revolution to the civilian sector, recognizing that the military could never muster the contribution to development and incremental advances that an emerging civilian IT sector, mobilized around the profits from an evolving innovation wave, could invest. So in IT DARPA played the role of innovation sponsor, enabling DOD to subsequently leverage the IT technologies it needed from investments at scale from the private sector.

Thus DARPA directly inherited the 'connected science' and 'technology challenge' models of the Rad Lab and Los Alamos advocated by Bush, Loomis, Dubridge, and Oppenheimer. 'Great group' innovation theory (Bennis and Ward Biederman 1997: 1–30, 196–218) posits that innovation occurs at the face-to-face levels in groups, no longer solo inventors, and these groups follow common organizational rule sets. Behind these 'great groups' lies a supporting innovation ecosystem based at the institutional level above the personal level. Both are required for innovation to occur. Unlike the Rad Lab and Los Alamos, which operated at the great group personal level, or NSF or NIH, which operate at the institutional level, DARPA has operated at both the institutional and personal levels of innovation. It plays an institutional innovation support role but has also consciously fostered great groups. DARPA has been both an innovation actor and an innovation enabler. DARPA became a bridge organization connecting the two organizational elements, institutional and personal, behind innovation, unlike any other R&D entity previously utilized by government.

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:[12]

- *Small and flexible:* DARPA consists of only 100–150 professionals. Some have referred to DARPA as '100 geniuses connected by a travel agent'.
- *Flat:* this is a flat, non-hierarchical organization, with empowered program managers.
- *Right–left challenge model:* this is a challenge-based 'right–left' research model.
- *Emphasis:* this is on selecting highly talented, entrepreneurial program managers often with both academic and industry experience who serve for a limited (3–5 year) period.
- *No labs:* research is performed entirely by outside performers, with no internal research laboratory.
- *Acceptance of risk:* projects focus on the 'high-risk/high payoff' motif, 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 a 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. Although largely outside the bureaucracy, it tries to maintain a lifeline back to senior DOD administrators for support on technology implementation.
- *Hybrid model:* DARPA often puts small, innovative firms and university researchers together on the same project so that firms have access to breakthrough science and researchers see pathways to implementation.
- *Teams and networks:* at its best, DARPA creates and sustains highly talented teams of researchers—great groups—highly collaborative and networked around the challenge model.
- *Acceptance of failure:* at its best, DARPA pursues a high-risk model for breakthrough opportunities and is very tolerant of failure if the payoff from potential success is great enough.
- *Orientation to revolutionary breakthroughs in a connected approach*: DARPA is focused on radical innovation rather than incremental innovation. It emphasizes high-risk investment, moves from fundamental technological advances to prototyping, and then passes the production stage to the armed services or the commercial sector.
- *A technology visioning process:* as opposed incremental step taking, occurs at the front of DARPA's research nurturing process.[13]

DARPA marked a return to Vannevar Bush's initial 'connected science' approach, but it was more. From an institutional innovation perspective, DARPA is a connected model, crossing the barriers between innovation stages from research to implementation, but also making an organizational link between the face-to-face group level of innovation and an innovation enabling institution. In contrast to the civilian R&D agencies focused on the initial stage, research, the DOD operated an innovation system that spanned the full spectrum of the innovation pipeline, supporting each stage, from research, to development, to prototype, to demonstration, to test bed, and often using its procurement power for initial product market creation. DARPA was part of a defense innovation system—it was an entrepreneurial innovator within DOD, but often relied on the military services (and in the case of IT, the private sector) for the follow-on stages to foster implementation.[14]

3. The 1970–90 competitiveness period

Vannevar Bush's basic research pipeline model, as discussed above, institutionalized a disconnect between research and later stage development over most of the US innovation system, making the handover to commercialization very difficult, compared to Bush's wartime connected approach. As noted, the arrival of DARPA showed that the defense innovation sector was moving away from this. That shift expanded beyond defense in the late 1980s. As the USA entered that period of heightened economic competitiveness over technology advance with Japan and Germany, concerns grew that, although the USA was originating the leading innovations, because of this pipeline disconnect, it was limited in its ability to commercialize them (Hughes 2004).

Japan had implemented a highly innovative model for manufacturing, built around technology advances and processes that drove a quality imperative and was having much more success in commercializing incremental technology advances than the USA.[15] Following World War II, the USA had organized its economy around a comparative innovation advantage and its innovation system, particularly its capacity for radical or breakthrough innovation nurtured through Bush's pipeline model, as opposed to incremental innovation, remained world leading in the 1980s and early 1990s. The 1980s problem for the US innovation system became known as the 'valley of death' because it focused on the gap between research and late-stage development (Branscomb and Auerswald 2002). Five new institutional models were adopted in this period to bridge this valley:

- *The Bayh–Dole Act* was passed in 1980, (USC 200–212) and was the first of the new generation of competitiveness legislation. Prior to this Act the federal government held title to the results of federally-funded research. Since the job of the federal government was not technology implementation, historically the government had done very little with the fruit of its support. The Act shifted ownership of federally-funded research results to the universities where the research was executed, giving universities a stake in its commercialization. Typically, the universities shared these rights with the researcher inventors on their faculties and in their labs, giving them an incentive to implement their ideas. The Act is generally viewed as a significant success,[16] enhancing the role of universities in what is termed here 'connected' science and giving them a stake in their regional economies. Gradually, universities formed technology transfer offices and began to build innovation support systems to assist their researchers and connect with regional firms, a process that is still ongoing.[17] The Act helped push both universities and their researchers further down the innovation pipeline toward technology development and company creation, not only research. The university increasingly became an implementation actor as well as a research actor.
- *The Manufacturing Extension Partnership* (MEP) was authorized in 1988,[18] based on the success of the longstanding agriculture extension program. It aimed to bring the latest manufacturing technologies and processes to small manufacturers around the nation, since small firms were increasingly dominating US manufacturing. It aided such manufacturers by advising on the latest manufacturing advances to foster productivity gains, thus assisting them across a 'valley of death' in this field. MEP formed extension centers in every state. The states shared costs, backed-up by a small Department of Commerce headquarters staff charged with program evaluations and transmission of best practices to the centers. MEP's national network has a federal funding base of around $100 million annually plus the approximately $200 million this leverages from the state and local resources. It now consists of 59 centers employing some 1,600 manufacturing specialists experienced in the needs of small manufacturing firms. For the past 20 years, the centers have worked with thousands of manufacturers, and MEP studies maintain the centers, deliver some $1.44 billion in cost savings annually and $10.5 billion in increased or retained sales per year to small manufacturers.[19] While some centers are inevitably stronger than others, the overall program has received positive evaluations, and it has received solid political support and sustained stable funding from Congress.
- *The Small Business Innovation Research* (SBIR) program was a second successful 'valley of death' program model.[20] It offered competitive R&D grant funding to small and start-up companies, administered through Small Business Administration (SBA), which also

supervises a related program, the Small Business Technology Transfer (STTR) Program. These two competitive programs aim to ensure that small, high-tech, innovative businesses are a part of the federal government's R&D efforts. Eleven federal departments participate in the SBIR program through required set-asides of their R&D funding; five departments participate in the STTR program. The two programs award over $2 billion to small businesses annually. SBIR has provided initial funding for many of the most noted technology start-up firms of the past 25 years: few new firms consider the start-up process without applying.

- *The Advanced Technology Program* (ATP, renamed and restructured in 2007 as the Technology Investment Program (TIP)),[21] is the third of the trio of 'valley of death' programs from the 1980s. It was formed in 1988 in the Department of Commerce's National Institute of Standards and Technology (NIST) program to fund a broad base of high-risk, high-reward R&D undertaken by industry. ATP reached some $200 million in annual grants during the early Clinton years, with the Administration seeking further major increases, but it was gradually defunded by Congress, with funding halted in 2011. Widely studied as a strong substantive model for technology innovation,[22] it was not tied to a particular agency mission but instead provided general R&D assistance to companies, so lacked the political support that mission-based research efforts have been able to obtain.
- *Sematech*. In the 1980s the US semiconductor industry faced a massive challenge from Japanese competitors who began to dominate market share through lower cost, higher quality chip production systems. With initial leadership from Intel's Robert Noyce and later William Spencer, in 1987 the industry organized a collaboration also tied to semiconductor equipment makers which worked systematically to improve chip manufacturing processes. DARPA matched industry Sematech funding until 1996. The effort reversed many industry production problems (Browning and Shetler 2000; Berlin 2005; Hof 2011) and the US industry continues as a world leader. Sematech also placed the industry on a unified technology roadmap to meet the relentless technical challenges of staying on Moore's Law, a task that Sematech continues to perform. Sematech became perhaps the most noted model of successful industry–university–government collaboration.

The USA was able to surpass its competitors and step past these competitiveness battles in the 1990s. These programs helped, but the underlying story was that after a multi-decade gestation period, where DARPA played a keystone role, the USA was able to move out of its confrontation over manufacturing with Japan and Germany and bring on a major innovation wave[23]—the IT revolution—in the early 1990s. It was transformative: the US economy created a net 22 million jobs in the 1990s, or 2.2 million a year. On top of IT the USA also added a smaller biotechnology wave. By the end of that decade leadership in those waves placed the USA strongly ahead of competitive economies. Its economy became the envy of the world. Despite the institutional innovation of the 1980s, the USA, flush with its innovation success which stemmed from earlier R&D investments, dropped its focus on innovation organization for a decade. So the 80s marked a shift in its innovation organizations so that these could act further down the innovation pipeline, but left this shift largely incomplete. Thus, when the IT and biotechnology waves went through bubbles as innovation waves inevitably do, and their growth moderated as these new sectors started to mature, the USA again faced innovation structure problems comparable to those it faced in the 1970s and 1980s.

4. ARPA-E: The new generation energy innovation institution

The DOE's efforts to bring on energy innovation traditionally focused on the front end of the innovation pipeline—on the R&D side.[24] In particular, the Office of Science, its major research program, has followed Vannevar Bush's basic research model. Programs on the back end—technology demonstration, testing, commercialization and deployment—were attempted by the DOE in areas such as synfuels during the Carter Administration, but failed after the collapse in oil prices in the early Reagan era. DOE was burned in this process (Deutsch 2005) and has been very reluctant to reinitiate it and is limited by political ideology that discourages a governmental role in later stage innovation in non-defense areas. While the DOD operates at all stages of the innovation pipeline, from research through initial market creation, the DOE halts at the prototype stage. It is an incomplete innovation system, disconnected from later innovation implementation stages. As DOE faced the challenge in the 2000s of energy security and climate change, this greatly complicated the mission of launching new energy technologies. It created the further problem in the energy area that DOE is not fully focused on: the problem of 'technology launch'.[25]

While the 'valley of death' has been the major preoccupation of science and technology policy for the past two decades, energy, as a 'legacy sector'—an established, complex, politically and economically powerful, technologically locked-in sector—presents an additional problem. The energy sector operates in an established political–economic–technological paradigm, and that paradigm must be altered if a new reduced carbon energy system is to prevail. Thus, even if the valley of death in energy—the gap between research and development—is surmounted, a deep problem remains. Because most new energy technologies are components in larger established systems (e.g. advanced batteries are components in cars, enhanced geothermal technology must fit into existing utility systems) they must launch into these established sectors and be price competitive from the moment of launch. Innovation in a complex, established sector presents problems very different from standing up technology advances in new, unoccupied, 'frontier' sectors like IT or biotechnology (Bonvillian and Weiss 2009; Weiss and Bonvillian 2011) where its 'new functionality' allows the new entrant technology to charge a premium price initially, then drive down the production cost curve over time.

To reiterate, launching new technology in a legacy sector like energy where new technologies initially do not offer new functionality—electricity in a home is the same to the consumer whether derived from coal or solar—means they must be competitive with existing technologies at the outset. Although DOE has formed several innovative new innovation elements, including energy frontier research centers and energy innovation hubs, they are still organized around the valley of death problem. They are not designed to encompass the technology launch task.[26] As tough as crossing the valley of death in energy is, reaching the point of market launch on the back end of the innovation is even harder.

4.1 The ARPA-E design: Incorporating the DARPA rule set

An exception is Advanced Research Projects Agency-Energy (ARPA-E),[27] which, although a breakthrough-oriented R&D agency, consciously attempts to move much further down the development pipeline. ARPA-E was recommended in the 'Rising Above the Gathering Storm' report (National Academies of Sciences 2007) by thought leaders such as Norman Augustine, Charles Vest, and Steven Chu (later Energy Secretary) (Bonvillian 2006) and strongly backed by the then-Chair of the House Science Committee, Rep. Bart Gordon (Democrat-TN), who assured the passage of authorization legislation[28] and its initial funding in 2009. It was consciously designed by Congress to apply the DARPA model to the new energy technology sector. Its roughly $200 million in annual funding makes it about the size of a single DARPA program office. It has emphasized speed—rapidly moving research breakthroughs into technologies, through a process it labels 'envision–engage–evaluate–establish–execute'.

ARPA-E has incorporated the well-known elements in the DARPA rule set cited above, including:

- a flat, non-hierarchical organization
- program directors (PDs) are 'empowered' with authority and discretion to administer a portfolio of projects in a related energy field
- process of project approval is streamlined
- a 'right–left' research model, where they contemplate the technology breakthroughs they seek to have emerge from the right end of the pipeline, then go back to the left side of the pipeline for research that will achieve that goal
- a challenge-based research model is used which seeks research advances that will meet significant technology challenges
- they aim at revolutionary breakthroughs that could be transformative of an energy sector.

Like DARPA, ARPA-E's PDs (the equivalent of DARPA program managers) are highly-respected, technically talented, world-class talent, typically with experience in both academic research and in industry, and ARPA-E has a broad waiver of civil service hiring authority to hire them quickly that may be without precedent in the federal government. ARPA-E's research program is organized around the 3–5-year terms of its PDs, thus, the project duration yardstick is the life of the PD. This means that ARPA-E must forego much long-term research. It must build its project portfolio by seeking breakthroughs that can move to prototype in—for science—a relatively short period. It therefore aims, like DARPA, at innovation acceleration: projects that can move from idea to prototype in the program life of its program managers. ARPA-E also has DARPA's highly flexible contracting authority, so-called 'other transactions authority' to quickly transact research contracts outside of the cumbersome federal procurement system.

Like DARPA, ARPA-E is also instituting the 'hybrid' model, providing funding support for both academic researchers and small companies. This tends to improve the handover from research to development by combining entities from each space, easing technology transition. Like DARPA, ARPA-E has worked from an island/bridge model[29] for connecting to its federal agency bureaucracy. The best model historically has been to put the innovation entity on a protected 'island' free to experiment, apart from contending bureaucracies: 'the suits'. As ARPA-E was set up within DOE, it has required both isolation and protection from rival R&D agencies and the notorious bureaucratic culture at DOE that may fight it for funding and curtail the independence it requires. Because it reports directly to the Secretary, it also has a 'bridge' back to the top DOE leadership to assure its place in DOE's R&D. Overall, ARPA-E aims, like DARPA, to operate at both of the two faces of innovation: at the institutional level, providing support for innovation, and at the personal, face-to-face level enabling innovation 'great groups'.

4.2 New elements at ARPA-E: The implementation stage

But ARPA-E cannot be a simple clone of DARPA because it faces a very different technology landscape than

DARPA. DARPA has been able to launch its technologies into two territories that simplified its tasks. First, it has often been able to place its technologies into the procurement programs of the military services. In this approach, the military is able to serve as the test bed and initial 'first' market for new technologies emerging from DARPA. Second, DARPA launches its technologies into civilian sectors—the IT sector it helped create is the most noteworthy—which are technology frontiers, enabling 'open space' technology launch.

In contrast, the energy sector facing ARPA-E technologies is occupied territory not open space: energy is already a complex established legacy sector. Given its very different launch landscape, ARPA-E is learning to vary its organizational model, not simply replicating DARPA, but adding its own elements appropriate to the complex energy sector which it concentrates on. While ARPA-E has developed a number of creative institutional features, the most noteworthy for our purposes concern the technology implementation stage.

4.3 The ARPA-E focus on technology implementation

Because of its difficult task in launching technology into the complex, established legacy sector of energy. ARPA-E has taken steps to assist in taking its technology to implementation, commercialization and deployment:

- *ARPA-E PDs:* consider the implementation process for technologies they are considering; before they fund a project they evaluate the technology development 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. They both select technologies that can move within range of commercialization, and build elements into the R&D program to drive down the cost of the technology. This is a new step for R&D agencies. The effort is aided by the fact that ARPA-E PDs have a rich mix of academic and commercial sector experience.
- *'In-reach' within DOE:* ARPA-E has worked to build ties with applied programs in DOE so that these agencies can be ready to pick up ARPA-E projects and move them into the applied, later stage development programs they run. ARPA-E's PDs have found that key to this DOE 'in-reach' is building relationships between PDs and applied line scientists and technologists in the applied entities, particularly the Energy Efficiency and Renewable Energy, Fossil Energy and the Electricity Offices. This is a bottom-up connection process.
- *Building ties to DOD for test beds and initial markets.* Although DOE does limited work beyond the prototype stage, DOD works at all the innovation stages and has major procurement programs and energy efficiency needs—it is a logical implementation partner for ARPA-E. The two agencies have a Memorandum of Understanding and DOD and ARPA-E have begun to act as partners on projects. ARPA-E has staff with significant defense contractor experience (on the 'commercialization team', see discussion below) and the potential role of DOD to test, validate and to offer an initial market for new energy technologies is well understood at ARPA-E.
- *Commercialization team:* Unique among R&D agencies, ARPA-E has assembled a separate staff team ('technology-to-market advisors') working full time to promote implementation and commercial advances for ARPA-E technologies. These team members work with particular PDs on the most promising technologies emerging from their portfolios. The tactics this team develops in implementing technologies can include: creating follow-on approaches for ARPA-E funded technologies through in-reach with DOE applied programs, connections to DOD test beds and procurement, and, particularly, connections to venture funding, financing and interested company collaborators, or combinations of these. Their work includes identifying first markets and market niches for ARPA-E technologies.
- *'Halo effect':* ARPA-E is consciously taking advantage of the 'halo effect' where venture and commercial firms move toward the commercialization of the technologies that are selected by ARPA-E as promising. In other words, the private sector views the ARPA-E project selection process as rigorous and sound, so it is prepared to fund projects emerging from that process. DARPA has long relied on this effect. Naturally, the venture or financing firm will perform its 'due diligence', but ARPA-E's selection helps to identify and validate a candidate technology.
- *Connecting to the industry 'stage gate' process:* The stage gate process is used by most major companies in some form in the management of their R&D and technology development. In this approach, candidate technology projects are reevaluated at each stage of development, weeded-out and only what appear to be the most promising from a commercial success perspective move to the next stage. This is not a process that ARPA-E employs. Like DARPA (as discussed above), it places technology visioning up front in its process and adopts a high-risk/high-rewards approach to meet the technology vision. ARPA-E also works with its researchers to ensure that their technologies are in a format and condition to survive in the industry stage gate process. For academic researchers in particular, this is not a familiar process.
- *Consortia encouragement:* Aside from stage gate connections to industry, in a different type of outreach effort, ARPA-E is building an additional industry connection step between the firms and academics that it

> works with and the industries they must land in: consortia promotion. ARPA-E tries to pave the way for acceptance of its new technologies at firms by working to encourage companies that work in similar areas to talk to each other on common problems, including on technology solutions that APRA-E's current or prospective projects could present.

To summarize, ARPA-E has not only worked to replicate elements at DARPA, but it has attempted to build new elements in its innovation rule set as it confronts unique features of the 'legacy' energy sector where its technologies must land. Particularly interesting are the approaches it is applying in the implementing and deployment process for its technology advances, moving much further down the development pipeline than traditional R&D agencies. Will the ARPA-E model and the other new innovation elements at DOE enable an energy technology transformation? The across-the-board cutbacks in energy (and other) federal R&D through 'sequestration' in 2013 are reminiscent of the dramatic cutbacks in energy R&D at the advent of the Reagan Administration as oil prices fell. It remains to be seen whether technology advances in energy at ARPA-E, despite its new model, and elsewhere can be kept on track.

5. A new innovation model for advanced manufacturing?

Manufacturing remains a critical part of the US economy:[30] it contributes $1.7 trillion to the $15 trillion economy and employs 12 million (Bureau of Labor Statistics June 2013) in a total employed workforce of some 140 million. Manufacturing workers are paid substantially more than service sector workers, 20% higher than non-manufacturing workers (Helper et al. 2012). Growth economists tell us that 60% or more of historic US economic growth comes from technological and related innovation (Solow 2000), and manufacturing dominates the innovation system. Industrial firms employ 64% of US scientists and engineers, and this sector performs 70% of industrial R&D (Tassey 2010: 290). Thus the US manufacturing strength and the strength of its innovation system are directly linked.

Success in a highly competitive world rewards nations and regions that produce complex, value-added goods. While world trade in services is growing, world trade in goods is close to five times trade in services (Directorate-General for Trade 2012). Complex, high-value goods (including capital goods, industrial supplies, transport goods, and medicines) dominate US export value and a significant majority of its import value. The currency of world trade is in such advanced goods, and will remain so indefinitely. Yet, the USA was running a $500 billion trade deficit in manufactured goods in pre-recession 2007, and is now on track to soon return to that level. As of 2011, that total included a $100 billion deficit in advanced technology products (US Census Bureau 2011).

Will services offset the manufacturing decline? As services are some 80% of the US economy, cannot this trend simply continue? The problem is that the modest and gradual growth in its services trade surplus ($160 billion in pre-recession 2007) is dwarfed by the size and continuing growth of the deficit in goods: the former will not offset the latter anytime in the foreseeable future. Given the trade imbalance, it is hard to avoid the conclusion that the USA has been shifting to a consumption-led versus production-led economy. Arguably, it now has a consumption/production imbalance, with significant long-term economic consequences.

5.1 The 'innovate here/produce here' assumption

Since World War II, the US economy has been organized around leading the world in technological advance. It developed a comparative advantage over other nations in innovation, and as a result, it led all but one of the significant innovation waves of the 20th century. It led innovation waves in aviation, electronics, space, computing, the internet (Ruttan 2006) and biotechnology. Its operating assumption was that it would innovate and translate those innovations into products. By 'innovating here and producing here', the USA would realize the full range of economic gains from innovation at all the stages, from R&D, to demonstration and test beds, to initial market creation, to production at scale, and to the follow-on life cycle of the product. It worked—the USA became the richest economy the world had ever seen. For the past half-century the USA has been playing out economic growth theory—that the predominant factor in economic growth is technological and related innovation—and demonstrating that it works.

But in recent years, with the advent of a global economy, the 'innovate here/produce here' model no longer holds. In some industrial sectors, firms can now sever R&D and design from production. Codeable IT-based specifications for goods that are tied to software-controlled production equipment have enabled this 'distributed' manufacturing (Berger 2005). While manufacturing once had to be integrated and quite vertical, firms using the distributed model can innovate here and produce there. It appears this distributed model works well for many IT products, as well as for commodity products. Apple is the standard-bearer for this model, continuing to lead in dramatic IT innovations, but distributing virtually all its production to Asia.

However, there appear to be many sectors where the distributed model does not work, that still require a close connection between research, design and production. Capital goods, aerospace products, energy equipment, and complex pharmaceuticals appear to be examples of this phenomenon. In these sectors the production infrastructure provides constant feedback to the R&D–design infrastructure. Product innovation—incremental advance—is most efficient when tied to a close understanding and linkage to manufacturing processes. However, if R&D–design and production are tightly linked, the innovation stages—R&D and design—may have to follow production offshore. 'Produce there/innovate there' may be even more disruptive than 'innovate here/produce there'. These twin developments bring the economic foundations of the USA's innovation-based economic success into question.

The conclusion that there are critical links between innovation and production, developed in a series of significant manufacturing studies (President's Council of Advisors on Science and Technology 2012; Information Technology and Innovation Foundation 2012a; MIT 2013) that could affect US innovation as well as production capacity, has driven a new focus on advanced manufacturing. If the USA is to compete with Asian manufacturing powers, it must significantly increase manufacturing efficiency and productivity. This calls for a new 21st century type of manufacturing, with major technology and related process innovations.

5.2 National Manufacturing Innovation Institutes model

Are there new innovation institutional elements to this challenge? The Advanced Manufacturing Partnership (AMP), of 12 leading firms and six research universities named by the President, proposed in its report, and the Administration is now implementing, a new model, a National Network of Manufacturing Institutes (NNMIs).[31] The first of these institutes has now been awarded to a consortium of regional industries and research universities, with strong state support, based in Youngstown, OH, and three more such institutes have now been proposed.[32] What is this model?

The manufacturing institutes are to be organized around a particular strand of advanced manufacturing. For example, the Youngstown institute is to focus on 'additive manufacturing' (3D printing),[33] which is of significant interest to the aerospace industry. Other strands proposed by AMP included advanced materials, 'smart' manufacturing, advanced robotics, energy efficient production, and nanofabrication. The institutes are to be consortia between large and small producers, area universities and community colleges, with state and regional support matched by the federal government. They are to combine collaborative research around the advanced manufacturing technology, collaborative staffing between the participants, serve as training centers to develop a workforce fluent with the new technology, and nurture advanced manufacturing enabling technologies through research, development, prototyping and test beds (President's Council of Advisors on Science and Technology 2012; Information Technology and Innovation Foundation 2012b).

In short, they are to be a return to 'connected' innovation, incorporating post-research innovation stages previously outside the federal purview and tying the innovation actors together in a way not previously undertaken in the federal government outside the defense sector. They build on the Sematech consortia model, linking industry, universities, and government, reaching through the test bed stage, and aiming to encourage subsequent commercialization. Whether these proposed institutes scale up to have an effect on the production sector remains to be seen, but they represent a new stage in the federal innovation support role.[34]

6. Conclusions

The saga of US innovation organization since World War II spans four and possibly now five periods. It moves from the advent of the post-World War II basic research, 'disconnected science' model sponsored by Vannevar Bush, which characterized the group of R&D agencies formed or operating at the end of the war. This was followed by a period when the defense R&D agencies, which could not live with a disconnected model given Cold War realities, were required to recreate the 'connected' R&D model of World War II. This reached a peak in the Sputnik period when DARPA was founded. Then, in the height of the competitiveness (1970–90) with Japan and Germany, the USA began to return to the connected model in a series of new civilian research programs as well as in the defense sector.

With the advent of the energy security and climate challenge, a new, more 'connected' model was created within the DOE, often a bastion of the disconnected model, through ARPA-E. Finally, the most recent innovation organization development—the proposed NNMIs to deal with the advanced manufacturing challenges the USA faces—marks a return to the connected approach, almost a 180 degree turn away from the Bush *Endless Frontier* plan for US R&D organization. It is not that basic research is not important: it remains key to US strength in breakthrough innovation. However, the story of the recent decades of innovation organization is to complement that foundational approach with additional institutional elements that reach much further down the innovation pipeline to development and later innovation stages. The new model innovation organizations discussed here deserve ongoing scrutiny and pragmatic evaluation of their performance to refine these models.

Notes

1. Federally-funded applied research was undertaken prior to World War II at, for example, the US Coast

Survey, US Geological Survey, the Department of Agriculture, the Naval Research Laboratory and the National Advisory Committee on Aeronautics, but at a fraction of wartime and Cold War funding levels (Smith 1990: 16–35).

2. The term refers to economist Richard Nelson's portrayal of the network of R&D and related innovation institutions and support mechanisms, including in industry, government agencies and universities, that make up an innovation ecosystem (Nelson 1993: 3–21, 505–23).
3. The opening sections of this paper draw on the author's detailed discussions of these developments in Bonvillian (2009: 206–35; 2011: 303–12).
4. The pipeline model for basic research was first institutionalized at the Office of Naval Research (Sapolsky 1990: 9–18). It provided the foundational model for exploratory, basic research that evolved at the NSF, and certainly influenced the NIH, and the DOE's Office of Science.
5. It is well understood that innovation does not necessarily occur in an orderly series of sequential pipeline stages (Branscomb and Aueswald (2002) call it a 'Darwinian Sea'), but the analogy is widely used and does roughly capture the stages that must be completed for technology implementation, so it is used here.
6. Bush attempted to organize post-war science under a single entity, NSF, but a veto by President Truman delayed the NSF's formation until 1950, and other agencies evolved in the interim (Blanpied 1998; Mazuzan 1994).
7. The problems with this model are explored by Stokes (1997).
8. Bush chaired the Defense Research and Development Board in 1947–48. Bush (1970: 56–63) discusses his views of the use of atomic weapons against Japan. In the internal debate over whether to create a strong federal research program, he was well aware of the risk of federal control of universities. His model for NSF tried to create some distance between government and universities to limit that risk.
9. There was widespread support from the advisors to Office of Scientific Research and Development for the recommendations in *Endless Frontier* Bush (1970: 64).
10. This discussion is drawn from Bonvillian (2009).
11. For a full discussion of US innovation ideology, see Hart (1998).
12. This list is drawn from Defense Advanced Research Projects Agency (2003, 2005). A more detailed evaluation of DARPA's rule set is given by Bonvillian and Van Atta (2011).
13. See, on DARPA visioning process, Carleton (2010), pp. 62–116.
14. For a description of how DARPA has worked with other parts of DOD, see, Van Atta et al. (2003).
15. The oligopolistic nature of major US industries, especially the automotive industry, where international competitors began to gain major market share, also played a role. Oligopoly in some key sectors appears to have stifled innovation. For the history of oligopoly curtailing innovation, see Hart (1998: 83–116).
16. The Act's success is discussed is discussed in Bayh et al. (2009) and Roessner et al. (2009). Others take a more measured view: there was growing diversity in the university economic role before Bayh–Dole, so it played a standardizing role as much as a transformative one, and there were additional forces that helped push universities into playing a more active role in regional economies (Mowery et al. 2004).
17. For a discussion of one university's model 'innovation ecosystem' see Roberts and Easley (2009: 44–71).
18. See Public Law 100-519, Title I, Section 102(d) (24 October 1988); 102 Statute 2590; 15 US Codes Chapter 7, Section 278k (Regional Centers for the Transfer of Manufacturing Technology); 15 CFR Section 290.6 <http://www.mep.nist.gov/about-mep/legislative-history.htm> accessed 21 August 2013.
19. For further information on the MEP, see NIST (2013), About MEP <http://www.mep.nist.gov/about-mep/index.htm> 21 August, 2013. The MEP Program is evaluated in, National Academy of Public Administration, Thge NIST Manufacturing Extension Program, Report I (Sept. 2003), <http://www.nist.gov/mep/upload/napa_1-2.pdf> accessed 21 August 2013. A major National Academy study of MEP is pending, NAS, STEP Board, 21st Century Manufacturing, The role of MEP, <http://sites.nationalacademies.org/PGA/step/21st_Century_Manufacturing/index.htm> accessed 21 August 2013.
20. The SBIR program has been criticized for funding too many 'SBIR mills' that live off repeated SBIR awards not technology commercialization, and for less rigorous selection standards than the research it is in effect taxing for its funding. However, a series of more recent National Research Council reviews of agency programs support the program's role. See, for example, National Research Council (2008) and the Testimony of Charles W. Wesner, NRC STEP Board, on the SBIR Program Before the Senate Committee on Small Business and Entrepreneurship, 17 February 2011. <http://www7.nationalacademies.org/ocga/testimony/SBIR_Program.asp> accessed 21 August 2013.
21. Section 3012 of the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Sciences (COMPETES) Act, Public Law 110-69, 110th Congress, 1st Session (9 August 2007), repealed the ATP and reformed it as the TIP.

22. See for example, National Research Council (1999), Ruegg and Feller (2003), and studies and data referenced in National Institute of Standards and Technology (2013); Advanced Technology Program (2007) 'Gems and Success Stories' <http://www.atp.nist.gov/gems/listgems.htm> accessed 21 August 2013.
23. Innovation wave theory is explored in Perez (2002: 3–46) and Atkinson (2004: 3–40).
24. See discussion in Alic et al. (2010).
25. See discussion of the issues raised in this section in Weiss and Bonvillian (2009: 2, 28–36,151–61, 167–171).
26. However, the DOE Energy Efficiency and Renewable Energy (EERE) office's new 'Sunshot' research program is aimed at commercial cost targets to make solar Photovoltaics competitive with established energy sources, and funds industry research. (See <http://www.eere.energy.gov/solar/sunshot/> accessed 21 August 2013).
27. This section draws on a more detailed discussion in Bonvillian and Van Atta (2011). See more detailed references therein.
28. See US Code a16538, s amended by Section 5012 of Public Law 110-69 (HR 2272) and Section 904 of Public Law 111-358 (HR 5116).
29. This term is used in Bennis and Biederman (1997: 196–218).
30. Discussion in this section is drawn from Bonvillian (2012).
31. President's Council of Advisors on Science and Technology (2012: 18–24). NNMI was not the only AMP recommendation. It made a series of innovation recommendations, from an enhanced advanced manufacturing R&D effort around 11 candidate advanced technologies and processes to improved workforce training and engineering education in advanced production, emphasizing that a series of related steps were required.
32. White House Press Release, 9 May 2013 <http://1.usa.gov/YLbjOZ> accessed 21 August 2013. The proposed new institutes are to focus on digital ('smart') manufacturing and lightweight and new metals fabrication, both led by DOD, and new power electronics, to be led by DOE.
33. For a discussion of additive manufacturing, see *The Economist* (2012).
34. Space limits the ability to discuss all new innovation institutional models. Also of note are: In-Q-Tel (Yanuzzi (2000)) and I-ARPA (see <http://www.iarpa.gov/index.html> accessed 21 August 2013) in the intelligence arena, the recently-formed National Center for Advancing Translational Sciences (see <http://www.ncats.nih.gov/research/research.html> accessed 21 August 2013) at the NIH and SERDP and ESTCP, the DOD environmental R&D programs (see, <http://www.serdp.org>).

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