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THE CONNECTED SCIENCE MODEL FOR INNOVATION: THE DARPA ROLE

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INTRODUCTION – FUNDAMENTALS OF DEFENSE TECHNOLOGY DEVELOPMENT[1]

The rise of the U.S. innovation system in the second half of the 20th century was profoundly tied to U.S. World War 2 and Cold War defense science and technology investment.[2] However, this late 20th century military technology evolution is only part of a much bigger picture of innovation transformation. Growth economist Carlotta Perez argues that an industrial and therefore societal transformation has occurred roughly every half century, starting with the beginning

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[1] Major portions of this chapter appeared in William B. Bonvillian, Power Play, The DARPA Model and U.S. Energy Policy, *The American Interest*, Vol. II, No. 2 (Nov./Dec. 2006), pp. 39-48, and appear here by permission of that journal.

[2] Vernon W. Ruttan, *Is War Necessary for Economic Growth, Military Procurement and Technology Development* (New York: Oxford Univ. Press 2006).

of the industrial revolution in Britain in 1770.[3] These technology-based innovation cycles flow in long multi-decade waves. Arguably, not only do these waves transform economies and the way we organize societies around them, they transform military power as well; U.S. military leadership has paralleled its technological innovation leadership. Perez found that the U.S. led the last three innovation waves – the information technology revolution represents the latest. Will this leadership continue? At stake is not only economic leadership but U.S. military leadership.

In other words, for the U.S. there has been a deep interaction between war and technology – war has greatly influenced technology evolution, and the converse is also true. While this has been the case for centuries, this interaction has been accelerating. Defense technology cannot be discussed as though it is separate and apart from the technology that is driving the expansion of the economy – they are both part of the same technology paradigms. Military historian John Chambers has argued that few of the critical weapons that transformed 20th century warfare came from a specific doctrinal need or request of the military;[4] Instead, the availability of technology advances has driven doctrine. If technology innovation is a driving force in both U.S. economic progress and military superiority, and these elements have interacted, we need to understand the causal factors behind this innovation.

One factor involves critical institutions, which represent the space where research and talent combine, where the meeting between science and technology is best organized. Arguably, there are critical science and technology institutions that can introduce not simply inventions and applications, but significant elements of entire innovations systems. We will focus on aspects of the U.S. innovation system supported by the defense sector - particularly the Defense Advanced Research Projects Agency (DARPA). An Eisenhower creation, DARPA was the primary inheritor of the WW2 connected science model embodied in Los Alamos and MIT's Rad Lab. DARPA came to play a larger role than other U.S. R&D mission agencies in both the Cold War's defense technology and the private sector economy that interacted with it.[5] DARPA will be used as a tool to explore the deep interaction between U.S. military leadership and technology leadership. As we attempt to understand where DARPA came from, we will also ask where it goes next, particularly in IT, as a way of focusing on the continuing strength of the defense innovation system.

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[3] Carlota Perez, *Technological Revolutions and Financial Capital* (Edward Elgar 2002). See also, Robert D. Atkinson, *The Past and Future of America's Economy – Long Waves of Innovation that Power Cycles of Growth* (Edward Elgar 2004).

[4] John Chambers, ed., *The Oxford Companion to American Military History* (Oxford Univ. Press 1999) p. 791.

[5] Richard Van Atta, et al, Institute for Defense Analysis, *DARPA Technological Accomplishments, An Historical Review of Selected DARPA Projects* (Alexandria, Va.: IDA, 1991), James C. Goodwin, et al, *DARPA, Technology Transition* (Arlington, Va.: DARPA 1999) <http://www.darpa.mil/body/pdf/transition>.

ROLE OF TECHNOLOGY INNOVATION AND TALENT IN GROWTH

Defense and civilian sector innovation in the U.S. are part of one economic system; that system includes not only sharing the same technology paradigms but sharing the societal wealth – economic growth - thrown off by that economic system, which funds both the military and the technology it increasingly depends on for leadership. Therefore, we need to understand the nature of innovation in economic transformation. Keeping in mind the argument that economic growth has dramatically affected military transformation, what are the causal factors in economic growth?

To briefly summarize three plus decades of work in growth economics, professor of economics Robert Solow of MIT won the Nobel Prize in 1987 because he was profoundly dissatisfied with the growth model of classical economics, where growth was understood in a static model of the interaction between capital supply and labor supply. Solow posited a dynamic model, arguing that while capital and labor supply remained significant, there was a much bigger factor. Studying five decades of U.S. economic growth he found that more than half of this growth flowed from technological and related innovation.[6] He argued that growth rates aren't in an equlibrium but can be altered through innovation advance, with societal well-being expanding correspondingly. The key factor behind his growth through innovation thesis, his work suggests, was the research and development system. However, because technology development is complex and not easy to measure, he treated it as "exogenous" to the economy. Economist Paul M. Romer of Stamford University articulated what I will call a second direct growth factor.[7] If the first is Solow's technological innovation founded on R&D, Romer argued that technical knowledge drives economic growth, and that it is an "endogenous" element in the economy. The key factor standing behind this knowledge is science and technological talent, the "human capital engaged in research." He suggested a prospector theory of innovation – the nation or region that fields the largest number of well-trained prospectors will find the most gold, i.e., the most innovative advances.[8]

These two direct factors, in shorthand, talent and R&D, don't stand in isolation from each other, they are interacting parts of an intricate ecosystem of innovation. There are many other factors that are important parts of this system, elements that are more indirect, implicit, and peripheral to innovation advance than the two direct factors essential to economic growth posited above, but these indirect

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[6] Robert M. Solow, *Growth Theory, An Exposition* (New York, Oxford: Oxford Univ. Press, 2nd edition 2000), pp. ix-xxvi (Nobel Prize Lecture, Dec. 8, 1987) <http://nobelprize.org/nobel_prizes/economics/laureates/1987/solow-lecture.html>

[7] Paul Romer, Endogenous Technological Change, *Journal of Political Economy*, vol. 98, (1990), pp. 72-102.

[8] See discussion of Solow and Romer in, David Warsh, *Knowledge and the Wealth of Nations* (New York: W.W. Norton 2006).

factors are nonetheless ones that a society must also get right for innovation advance.

The list of indirect innovation factors is long and, because growth economics is relatively new to the economics scene, the metrics for understanding the interaction of these factors are largely unexplored. On the government side they include fiscal, tax, and monetary policy, trade policy, technology standards, technology transfer policies, government procurement, intellectual property protection, the legal and liability systems, regulatory controls, accounting standards, and export controls. On the private sector side, which in a capitalist enterprise must dominate innovation, they include investment capital, including angel, venture, IPO's, equity, and lending, markets, management principles and organization, talent compensation and reward and quality of plant and equipment. Keep in mind that that these direct and indirect innovation factors all interact and it is the interaction that is most important. Therefore they represent a common system for both economic and defense sector advance.[9]

IS THERE A THIRD DIRECT INNOVATION FACTOR?

In addition to the two direct and the numerous indirect innovation factors suggested above, arguably there is a third direct factor: the way that R&D and talent, in particular, come together to form an innovation system. In other words, if R&D is factor A, and talent is factor B, they form an interacting combination, AB, which in itself is a third factor, the meeting space for science and technology and the talent behind it. It is not enough to have the ingredients of R&D and talent, they have to come together in an effective way for a highly productive innovation system. We'll call this third factor innovation organization. Linking two factors together, AB, is

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[9] We have been discussing innovation in the context of economics, but growth economics, because it is founded on a dynamic model of innovation, has begun to break down the focus of economics, since the late 40's (neoclassical economics) on the mathematical modeling suited to analysis of limited numbers of variables in a closed equilibrium. Instead, as growth economist Brian Arthur has argued, innovation can create increasing returns not just diminishing returns, leading to transformational phase shifts in an economy. Growth economics requires not only the neo-classical economics of physics-like fundamental principles subject to formulaic proof, but an economics of complexity, where a rich array of interacting elements must be accounted for in systems that are not static but evolve. For example, if innovation organization is a key factor in innovation and therefore economic growth, this element pushes economics towards its original roots in the social sciences and away from neo-classical economic modeling which cannot fully capture organizational elements. This concept puts an orange in what economics has viewed as a mix of apples. In other words, growth economics is gradually broadening economics' explanatory depth and toolset to reach and understand complex systems, and the third innovation factor discussed below, innovation organization, arguably pushes it further in that direction. See, generally, M. Mitchell Waldrop, *Complexity, the Emerging Science at the Edge of Order and Chaos* (New York: Simon & Schuster 1992), pp. 144-148, 250-255, 284-313, 325-327. Since the author drafted this article and footnote in 2006, another book has been published discussing some of these points, Eric D. Beinhocker, *Origin of Wealth – Evolution, Complexity and the Radical Remaking of Economics* (Cambridge, MA: Harvard Bus. Sch. 2007).

shorthand in math for multiplying them; arguably, there is a multiplier factor here, too – the way R&D and talent join and are organized can be a multiplier for each. If innovation organization is a kind of multiplier for the two key direct innovation factors, then the way defense and civilian innovation systems organize R&D and talent, and the massive areas where the two systems overlap, will be profoundly determinative of innovation advance for the two systems, and therefore of economic and military leadership.

What does innovation organization look like? This factor must be seen and understood at least at two levels, the institutional level and the personal, face-to-face level. We will explore these in succession.

U.S. INNOVATION ORGANIZATION AT THE INSTITUTIONAL LEVEL

Governmental science and technology organization in the U.S. largely dates from WW2 and the immediate post-war. As suggested earlier, technology evolution in this country comes from a kind of "PushMi-Pullyu" relationship between civilian economic and defense sectors, and WW2 was a transformative period where the pressure for military technology advance later led to a dramatic economy-wide advance.

Vannevar Bush led this charge,[10] acting as President Roosevelt's personal science executive during the war. He was allied to a remarkable group of fellow science organizers, including Alfred Loomis, an investment banker and scientist, physicist Ernest Lawrence of Berkley, and two university presidents, James Conant of Harvard and Karl Compton of MIT. Successively, Bush created and took charge of the two leading organizing entities for U.S. science and technology, the National Defense Research Council (NDRC) and then the Office of Science Research and Development (OSRD). These became the coordinating entities for U.S. wartime R&D, creating crash research projects in critical areas, such as the Rad Lab at MIT and Los Alamos, and they and, in turn, insured interaction and coordination with a rich mix of research components. Influenced by the frustrations of his WW1 military research experience where technology breakthrough could not transition past bureaucratic barriers into defense products, Bush kept civilian science control of critical elements of defense research, insisting that his science teams stay out of uniform and separate from military bureaucratic hierarchies which he found unsuited to the close-knit interaction needed for technology progress.

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[10] G. Pascal Zachary, *Endless Frontier, Vannevar Bush, Engineer of the American Century* (Cambridge, MA: MIT Press 1999). See also, Jennet Conant, *Tuxedo Park* (New York: Simon and Shuster 2002)(biography of Alfred Loomis, founder of MIT's Rad Lab). For a discussion of U.S. pre-WW2 science organization see, David Hart, *Forged Consensus* (Princeton, NJ: Princeton Univ. Press 1998).

To summarize, Bush brought all defense research efforts under one loose coordinating tent, NDRC then OSRD, and set up flat, non-bureaucratic, interdisciplinary project teams oriented to major technology challenges, like radar and atomic weapons, as implementing task forces. He created "connected" science, where technology breakthroughs at the fundamental science stage were closely connected to the follow-on applied stages of development, prototyping and production, operating under what we will call a technological "challenge" model. Because Bush (and his ally Loomis) could go directly to the top for backing from Roosevelt, through Secretary of War Henry Stimson and Presidential Aide Harry Hopkins, Bush made his organizational model stick during the war, despite relentless military pressure, from the Navy in particular, to capture it.

Then, immediately after the war, he systematically dismantled his remarkable connected science creation.

Envisioning a period of world peace, convinced that the wartime levels of government science investment would be slashed, and probably wary of a permanent alliance between the military and science, Bush decided to try and salvage some residual level of federal science investment. He wrote the most influential polemic in U.S. science history, "The Endless Frontier," for Roosevelt, arguing that the federal government should fund basic research, which would deliver ongoing progress in economic well-being, national security and health to the country.[11] In other words, he proposed ending his model of connected science, and dropping his challenge model, in favor of making the federal role one of funding one stage of technology advance, exploratory basic research. His approach would become known as the "pipeline" model for science investment. The federal government would dump basic science into one end of an innovation pipeline, and somehow early and late state technology development and prototyping would occur inside the pipeline, with new technology products emerging, genie-like, at the end. Because he assembled a connected science model during WW2, Bush no doubt realized the deep connection problems in inherent this pipeline model, but likely felt that salvaging federal basic research investment was the best he could achieve in a period of anticipated peace.

He did argue that this basic research approach should be organized and coordinated under "one tent" to direct all the nation's research portfolios, proposing what would become the National Science Foundation (NSF). Because he wanted this entity controlled by a scientific elite separated from the nation's political leadership, Bush got into a battle with Roosevelt's successor, Harry Truman. In his typical feisty, take-charge way, Truman insisted that the scientific buck would stop on his desk not on some Brahmin scientist's desk, and that NSF appointments would be controlled by the President. Bush disagreed.

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[11] Vannevar Bush, *Science: The Endless Frontier* (Wash., DC: Government Printing Office 1945) p. 1-11 (FDR and Bush letters, Summary, Introduction) (Available at <http://www.nsf.gov/od/lpa/nsf50/vbush1945.htm>

Truman therefore vetoed Bush's NSF legislation, stalling its creation for another five years.[12] Meanwhile, science did not stand still. New agencies proliferated, and the outbreak of the Korean War led to a renewal of defense science efforts. By the time NSF was established and funded, its potential coordinating role had been bypassed. It also became a much smaller agency than Bush anticipated, only one among many. Despite Bush's support for one tent where scientific disciplines and agencies could coordinate their work, as they did in WW2, the U.S. thus adopted a highly decentralized model for its science endeavor.[13]

Bush's concept of federal funding focused on basic science did prevail, however, with most of the new science agencies adopting this model for the federal science role. These twin developments left U.S. science fragmented at the institutional level in two ways: overall science organization would be fragmented among numerous science agencies, and federal investment would be focused on only on one stage of technological development, exploratory basic research.[14] Remarkably, Bush left a legacy of two conflicting models for scientific organizational advance: the connected, challenge model of his WW2 institutions, which he dismantled after the war,[15] and the fundamental-science focused, disconnected, multi-headed model of post-war U.S. science institutional organization.

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[12] William A. Blanpied, Inventing U.S. Science Policy, *Physics Today*, 51 (2) (Feb. 1998), pp. 34-40 (post-WWII evolution of U.S. science organization and NSF); George Mazuzan, *NSF, A Brief History (1950-1985)* (Arlington, Va: NSF 88-16 1988) pp. 1-25 (history of NSF in the context of post-WWII science).
Available at <http://www.nsf.gov/pubs/stis1994/nsf8816/nsf8816.txt)>.

[13] It must be emphasized that there are major advantages to decentralized science. It creates a variety of pathways to science advance and a series of safety nets to ensure multiple routes can be explored. Since science success is largely unpredictable, the "science czar" approach risks major failures that a broad front of advance does not. Nonetheless, the U.S. largely lacks the ability to coordinate its science efforts across agencies particularly where advances that cut across disciplines require coordination and learning from networks.

[14] See discussion of these developments in, Donald E. Stokes, *Pasteur's Quadrant, Basic Science and Technological Innovation* (Wash., DC: Brookings Institution Press 1997).

[15] The term "dismantled" is used to indicate that the structure for science management in WW2 was ended, and many wartime science entities were shut down, including MIT's Rad Lab. Obviously, other existing science entities continued in operation, such as NACA, which Bush chaired before the war, and was an early example of a connected, challenge model approach. See, *Alex Roland, Model Research: The National Advisory Committee for Aeronautics, 1915-1958,* pp. 225-258 (Chapt. 10). <http://history.nasa.gov/SP-4103/>. However, even within DOD, the Office of Naval Research was largely stood up after the war around a fundamental science model. Harvey M. Sapolsky, *Science and the Navy – The History of the Office of Naval Research* (Princeton, NJ: Princeton Univ. Press 1990), pp. 9-81 (Chapts. 2-4).

SUMMARY OF THE INNOVATION ANALYTICAL FRAMEWORK

To summarize the discussion thus far, innovation is not only about R&D investment levels, it's about content and efficiency.[16] U.S. post-war policy institutionally severed R from D, which had been connected in the wartime model, and posited a pipeline theory of innovation where the federal government dumped research funding into one end of the pipeline, then mysterious things occurred within the innovation pipeline, then remarkable products emerged at the other end. Neoclassical economics, through the work of Robert Solow, came to realize the central role of innovation in economic growth but was unable to apply existing economic models to the mystery inside the pipeline, so treated innovation as "exogenous" to the economy. That response was ultimately unacceptable – it as though economics, after finally discovering the innovation monster in the economic growth room, then declined to look at it. So a group of growth economists, initially led by Paul Romer, gradually began to whittle away at the monster, treating it as "endogenous," slowly delineating its economic attributes. However, this delineation process still has barely begun.[17] Economic institutions still collect extensive data on the two factors classical economics tied to economic growth, capital supply and labor supply, and data on R&D investment totals; we have little data on the monster, the content and efficiency of the innovation system.[18] Few are searching for and analyzing the new factors and metrics for innovation evaluation. Interestingly, two decades after Solow won the Nobel Prize for identifying the innovation monster, the U.S. Department of Commerce has announced the need to begin an intensive data collection process around innovation.[19] The National Science Foundation, which has long collected data on innovation investment levels and science education,[20] has began an effort to look at data and analysis around innovation with a program entitled the Science of Science and Innovation Policy.

But what is the framework for the innovation metrics and analysis? Although we track R&D investment, what about the composition and efficiency factors? This paper attempts to identify some of the elements lurking inside the innovation

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[16] Gregory Tassey*, The Innovation Imperative* (Cheltenham, UK: Edward Elgar 2007), Chapts. 3, 7, 8.

[17] For a critical view of the progress of endogenous growth theory in economics, see Robert Solow, Toward a Macroeconomics of the Medium Run, *Journal of Economic Perspectives* (Winter 2000).

[18] Despite the emergence over two decades ago of growth economics and its doctrine that growth is predominantly innovation based, the two U.S. political parties are still largely organized around the old factors posited by classical economics as responsible for growth, capital supply and labor supply.

[19] U.S. Dept. of Commerce, *Innovation Measurement, Tracking the State of Innovation in the American Economy*, Report to the Sec. (Wash., DC: U.S. Dept. of Commerce Jan. 2008) <http://www.innovationmetrics.gov/Innovation%20Measurement%2001-08.pdf>; Michael Mandel, A Better Way to Track the Economy, A Groundbreaking Commerce Dept. Report Could Lead to New Yardsticks for Measuring Growth, *Business Week* (Jan. 28, 2008) p. 29.

[20] National Science Board, *Science and Engineering Indicators* (Arlington, Va: NSF 2006) <http://www.nsf.gov/statistics/seind06/toc.htm>.

pipeline. Following Solow and Romer, it argues, as noted, that R&D and talent (shorthand terms for their extended ideas) can be considered *two direct innovation factors*, indispensable to innovation, and are surrounded by an ecosystem of indirect factors, less critical but none the less significant.

This paper further posits that there is a *third direct innovation factor*, innovation organization, the space where the talent and R&D converge. An essential aspect of innovation organization requires evaluation at the institutional level. Summarized above is the brilliant success the U.S. experienced at the institutional level during WW2 with a connected science model built around technological challenges, formed under one organizational tent. The U.S., following the war, shifted to a highly decentralized model, scattering government-funded research among a series of mission agencies. It was predominantly a basic-science focused model, not connected science, and left what later became known as a "valley of death" between research and development stages, so the handoff from publicly-funded research and to private sector development lacked institutional bridging mechanisms. As we will see, the major exception to that U.S. institutional rule was DARPA.[21]

We turn now from a review of innovation at the institutional level to a second analytical perspective on innovation organization, innovation at the personal, face-to-face level. Following this review we will examine how these twin perspectives on innovation organization have operated within an arguably critical U.S. innovation organization, DARPA, evaluating how it has worked at both levels, institutional and personal.

INNOVATION SYSTEMS AT THE PERSONAL LEVEL – GREAT GROUPS

Innovation organization should be analyzed it the institutional level, as discussed above, but also requires understanding at the ground level, from the personal, face-to-face point of view. Innovation is different than scientific discovery or invention, which can involve solo operators. Instead, innovation requires taking both scientific discovery and invention and piling applications on a breakthrough invention or

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[21] This is not to assert that the fundamental science mission agencies dating from the 1940's have remained frozen in time. While the basic science mission remains paramount at agencies such as NSF, NIH and the DOE Office of Science, at the National Science Foundation, for example, there is funding not only for small individual investigator basic research but larger areas of interdisciplinary advance, such as nanotechnology, which can incorporate grand challenges. For example, NSF's issue workshops and similar organizing mechanisms bring in ideas for coordinated science-engineering advance for initial buy-in and research program design by fundamental and applied communities. As another example, NSF's engineering directorate supports engineering centers tying science advance to fundamental engineering advance. Somewhat similar efforts around interdisciplinary centers have evolved at NIH and DOE. The point remains that these functions supplement established fundamental science efforts.

group of inventions to create disruptive productivity gains that transform significant segments of an economy and/or defense system. So innovation is a third phase built on phases of discovery and invention. Innovation requires not only a process of creating connected science at the *institutional level*, it also must operate at the *personal level.* People are innovators, not simply the overall institutions where talent and R&D come together. Warren Bennis and Patricia Beiderman have argued that innovation, because it is much more complex than the earlier stages of discovery and invention, requires "great groups" not simply individuals.[22] Rycroft and Kash make a similar argument but use a different term: innovation requires collaborative networks[23] which can be less face-to-face and more virtual. As we look at innovation organization at the personal level, we will explore the rule sets for three sample "great groups" of innovators.

1) Edison's "Invention Factory" at Menlo Park, New Jersey

Thomas Edison formed the prototype for innovator great groups.[24] Edison placed his famous Menlo Park lab in a simple 100-foot long wooden frame building, a lab, on his New Jersey farm. In it he placed a team of a dozen or so artisans, mixing a wide range of skills with a few trained scientists. They worked intensely, sometimes 24/7, and took midnight breaks together, eating pies, reciting poems and singing songs. They mixed a range of disciplines and organize their intense effort around the challenge of electric light. They were a great group, highly collaborative. Great groups also require collaboration leaders and Edison was a remarkable team leader. They worked on the idea of filling the gap between electric poles with a filament placed in a vacuum tube. But that was only the breakthrough invention, not the innovation. To make their light usable, Edison and his team then had to invent much of the infrastructure for electricity – from generators to wiring to fire safety to the structure of a supporting electric utility industry. Edison and his team become inventors and innovators, visionaries and (as initiators of a network of companies with Wall Street backing) vision enablers.

Interestingly, as part of this process, Edison had to derive elements of electron theory to explain his results – his "Edison Effect" helped lead to atomic physics advances. There is a major lesson in this: science is not simply a linear pipeline going from basic to applied, it goes both ways: basic to applied and applied to basic. Menlo Park teaches us parts of the rule set for great groups. *It is organized around a challenge model, with the group trying to solve a specific challenge or goal; it applies an interdisciplinary mix of both practical and basic science to get there, and it uses a connected science*

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[22] Warren Bennis and Patricia Ward Beiderman, *Organizing Genius* (New York: Basic Books 1997).

[23] Robert W. Rycroft and Don E. Kash, Innovation Policy for Complex Technologies, *Issues in Science and Technology* (Fall 1999).

[24] See discussion in Sir Harold Evans, *They Made America* (Sloan Foundation Project, Little Brown 2005) pp. 152-171.

model, tying invention to innovation and incorporating all stages of innovation advance. The group is under Edison's clear leadership, and that leadership factor is vital, but it is a non-hierarchical, relatively flat, two-level, highly collaborative effort. The team mixes experimentalists and theorists, artisans and trained scientists and engineers, for a blend of experimental and theoretical capability and disciplines.

2) Alfred Loomis and the Rad Lab at MIT, 1940-1945

Alfred Loomis loved science but family needs compelled him to become lawyer; he combined his science and legal skills to become a leading Wall Street financier for the emerging electric utility industry in the 1920's.[25] Anticipating the market crash, he sold out in 1928 with his great fortune intact. He used it to pursue science, setting up his own private lab at his Tuxedo Park, New York estate in the '30's and assembling there a who's who of pre-war physics. Loomis' own field of study there was microwave physics. As WW2 loomed, Vannevar Bush, respecting Loomis' industrial organizing skills, asked him to join Roosevelt's NRDC to mobilize science for the war.

Because the American military is initially uninterested, the British handed over to Loomis a suitcase with their secrets to microwave radar in his penthouse in the Shoreham Hotel in Washington in 1940. As the Battle of Britain raged, Loomis' microwave expertise enabled him to grasp immediately that this was a war winning technology for air warfare. He promptly persuaded his cousin and mentor, Secretary of War Henry Stimson, that this technology must be developed and exploited without delay. With Bush's and Roosevelt's immediate approval, Loomis within two weeks stood up the Radiation Laboratory (Rad Lab) at MIT. Because he knew them from his Tuxedo Park lab, Loomis and his ally and friend Ernest Lawrence of Berkeley called in the whole talent base of U.S. physics to join the Rad Lab, and nearly all came. Because the government was not used to establishing major labs literally overnight, Loomis personally funded the startup while government approvals and procurement caught up.

The Rad Lab was non-hierarchical and flat, with only two levels, project managers and project teams, each devoted to a particular technology path. It was characterized by intense work, often around the clock, and by high spirits and morale. Loomis and Bush purposely kept it out of the military. The Rad Lab used a talent base with a mix of science disciplines and technology skills, it was highly collaborative, it was organized around the challenge model, and it used connected science, moving from fundamental breakthrough to development, prototyping and initial production. Interestingly, the Rad Lab organizational model was systematically adopted at Los Alamos, and ten leading Rad Lab scientists shifted to Los Alamos to

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[25] Details from Loomis' biography, Jennet Conant*, Tuxedo Park*, op cit.

implement it.[26] The Rad lab developed great advances in microwave radar and the proximity fuse, technologies vital to success for the allies. Eight Nobel prizewinners came out of the Rad Lab and it ended up laying the foundations for important parts of modern electronics. It also embodied another feature key to successful great groups – through Loomis and Bush, the Rad Lab had direct access to the top decisionmakers able to mandate the execution and adaptation of its findings, Stimson and Roosevelt.

3) The Transistor Team at Bell Labs (1947)

Bell Labs' Murray Hill facility was consciously set in the New Jersey countryside after Edison's Menlo Park model and also drew from the great military labs of WW2, the Rad Lab and Los Alamos. AT&T's R&D Vice President, Mervin Kelly and his lead researcher, William Shockley, wanted a solid state physics team of fifty scientists and technicians from various fields with capability for fundamental research leading to practical applications. Their task was to develop a solid state physics-based replacement for vacuum tubes so that AT&T's switching capability could continue to advance telephone speed and capacity. John Bardeen and Walter Brattain, two of the leading solid state physics researchers who joined this team, developed a profoundly close collaboration, where the scientific and personal skills of one matched the other's – one a theorist, the other an experimentalist, one outgoing, the other reflective. They were social friends and held a strong mutual respect. Backed-up by Bell Labs' deep industrial technical support system, with the latest equipment and very strong technical staff, the two entered into a "magic month" from mid-November to December 16, 1947, and developed the first transistor.

As Bardeen's biographers put it, "The solid-state group divided up the tasks: Brattain studied surface properties such as contact potential; Pearson looked at bulk properties such as the mobility of holes and electrons; and Gibney contributed his knowledge of the physical chemistry of surfaces. Bardeen and Shockley followed the work of all members, offering suggestions and conceptualizing the work."[27] Brattain later commented, "It was probably one of the greatest research teams ever pulled together on a problem…. I cannot overemphasize the rapport of this group. We would meet together to discuss important steps almost on the spur of the moment of an afternoon. We would discuss things freely. I think many of us had ideas in these discussion groups, one person's remarks suggesting an idea to another. We went to the heart of many things during the existence of this group, and always when

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[26] See discussion of Los Alamos in Martin Sherwin and Kai Bird, *American Prometheus, The Triumph and Tragedy of J. Robert Openheimer* (New York: Alfred A. Knopf 2005) and Jennet Conant, *109 East Palace* (New York: Simon and Shuster 2005).

[27] Lillian Huddleson and Vicki Daitch, *True Genius – The Life and Science of John Bardeen* (Wash., DC: Joseph Henry Press of the National Academies of Sciences 2002) pp. 127-128.

we got to the place where something needed to be done, experimental or theoretical, there was never any question as to who was the appropriate man in the group to do it."[28]

Unfortunately, Shockley's reaction wrecked further working collaboration in the group. He attempted to garner credit for Bardeen's and Brattain's work, then worked secretly at his home designing a further breakthrough improvement, where a semiconductor "sandwich" replaced the transistor's electrical contact point, without telling the rest of the group. Before distrust descended, however, the group followed many of the rules of the other groups cited above – it was highly talented, relatively non-hierarchial, organizationally flat with essentially two levels, highly collaborative, and brought to bear a range of expertise and disciplines, including theorists and experimentalists, with each participant working in his strongest skill area. It was organized on a challenge model and the connection to AT&T's VP Mervin Kelly assured a tie to a decisionmaker who could enable development of breakthroughs. The group traded ideas on a continuous basis, meeting frequently with each providing thoughts to assist the others' progress, and Bardeen and Shockley played a leadership role by continually moving conceptual ideas among the group.

Many of the organizational features of these three "great groups" are common to others, including the development of atomic weapons at Los Alamos, the integrated circuit and microchip at Fairchild Semiconductor and Intel, the aeronautics and stealth advances at Lockheed's Skunk Works, the personal computer at Xerox Parc and Apple, biotech at Genentech and Craig Venter's genomics projects.[29] These projects are not unique. A venture capitalist has commented that he looks for these same kinds of characteristics every time he funds a startup. To summarize, a common rule set seems to characterize successful innovation at the personal and face-to-face level; the rules include ensuring: a highly-collaborative team or group of great talent; a non-hierarchical, flat and democratic structure where all can contribute; a cross-disciplinary talent mix, including experimental and theoretical skills sets networked to the best thinking in relevant areas; organization around a challenge model; using a connected science model able to move breakthroughs across fundamental, applied, development and prototype stages; cooperative,

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[28] Ibid.

[29] Kai Bird and Martin Sherwin, *American Prometheus, op cit*,, pp. 205-228, 255-259, 268-285, 293-297; Jennet Conant, 109 East Palace, op cit, pp. 106, 108, 110, 255; Leslie Berlin, The Man Behind the Microchip, Robert Noyce and the Invention of Silicon Valley (Oxford Univ. Press 2005), Chapt.'s 3-8; Ben Rich, Skunkworks (Back Bay Books 1996); Sir Harold Evans, They Made America, op cit, pp. 420-431 (Boyer and Swanson found Genetech and start biotech); Bennis and Biederman, op cit, pp. 63-86 (Xerox Parc and Apple); Daniel S. Morrow, Dr. J. Craig Venter – Oral History, (Computer World Honors Program April 21, 2003) <cwheroes.org/archives/histories/venter> pp. 3-53, 56-58; J. Craig Venter, A Life Decoded (Viking 2007) Chapt. 12.

collaborative leaders able to promote intense, high morale; and direct access to top decisionmakers able to implement the group's findings.[30]

DARPA AS A UNIQUE MODEL – COMBINING INSTITUTIONAL CONNECTEDNESS AND GREAT GROUPS

We have discussed the concept of innovation organization as a third direct innovation factor, and noted that it operates in macro and micro ways, at both the institutional level and the personal level. Our focus now shifts to the Defense Department's Defense Advanced Research Projects Agency. 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 America's Sputnik failure, DARPA became a unique entity. In many ways, DARPA directly inherited the connected science, challenge and great group organization models of the Rad Lab and Los Alamos stood up by Bush, Loomis and Oppenheimer. However, unlike the personal-level models discussed above, DARPA has operated at *both* the institutional and personal levels. DARPA became a bridge organization connecting these two institutional and personal organizational elements, unlike any other R&D entity stood up in government.

J.C.R. LICKLIDER AND THE BEGINNINGS OF THE DARPA MODEL

The DARPA model is perhaps best illustrated by one of its most successful practitioners, J.C.R. Licklider, who, as an office director at DARPA working with and founding a series of great technology teams, laid the foundations for two of the 20th century's technology revolutions, personal computing and the internet.[31] In 1960, Licklider, trained in psychology with a background in physics and mathematics, wrote about what he called the "Man-Machine Interface" and "Human-Computer Symbiosis": "The hope is that in not too many years, human brains and computing machines will be coupled together very tightly, and that the resulting partnership will think as no human brain has ever thought."[32] By 1960, Licklider envisioned timesharing as a path to real time personal computing (as opposed to the then-dominant main-frame computing), digital libraries, the internet (the "Intergalatic

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[30] For discussion of additional great groups and variations in this suggested rule set, see Bennis and Biederman, *op cit*.

[31] Discussion in this section drawn from Licklider's biography by M.Mitchell Waldrop, The Dream Machine (Viking 2001). For discussions of DARPA's and DOD's central role in fostering the many phases of the IT revolution, see, Ruttan, *op cit*, pp. 91-129; Glenn R. Fong, ARPA Does Windows, the Defense Underpinning of the PC Revolution, Business and Politics, Vol. 3, No. 3 (2001); National Research Council, Science and Telecommunications Board, Funding a Revolution, Government Support for Computing Research (National Academy Press, Wash., D.C. 1999), pp. 85-187.

[32] Licklider, "Man-Computer Symbiosis", IRE Transactions on Human Factors in Electronics (March 1960).

Computer Network"), what we now call the world wide web, and most of the features, like computer graphing, simulations and modeling, that we are still evolving to implement those revolutions. Licklider was hired by DARPA[33] to work on what was being called the "command and control" problem, and then that problem took off in importance. Because Kennedy and MacNamara became deeply frustrated with a profound command and control problem - their inability to obtain and analyze real time data and interact with on-scene military commanders during the Cuban Missile Crisis - DARPA gave Licklider major resources to tackle it. It was the rare case of the visionary being placed in the position of vision-enabler. Strongly backed by noted early DARPA Directors Jack Ruina and Charles Herzfeld, Licklider found, selected, funded, organized and stood up a remarkable support network of early information technology researchers at universities and firms that over time built personal computing and the internet. He served at two different periods in DARPA.

At the institutional organization level, DARPA and Licklider became a collaborative force among the Defense Department's research agencies controlled by the services, using DARPA IT investments to leverage participation by the agencies to solve common problems under connected science and challenge models. DARPA and Licklider also kept their own research bureaucracy to a bare bones minimum, using the service R&D agencies to carry out project management and administrative tasks, so that DARPA's efforts created co-ownership with the service R&D stovepipes. Institutionally, although it certainly did not always succeed, DARPA attempted to become a research supporter and collaborator, not a rival competitor to the DOD service research establishment.[34]

At the personal level of innovation organization, Licklider created a remarkable base of information technology talent both within DAPRA and in a collaborative network of great research groups around the country. This team of apostles, including Doug Engelbart, Ivan Sutherland, Robert Taylor, Larry Roberts, Vint Cerf, Robert Kahn, and their many comrades, are a who's who of personal computing and internet history. Because of ongoing progress, DARPA was willing to be patient and able to look at the long term in these IT talent and R&D investments in a way that corporations and venture capital firms are not structured to undertake.[35] Licklider's DARPA model was also not a flash in the pan – internally it

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[33] DARPA Director Jack Ruina later concluded that hiring Licklider was his most significant act at DARPA. In seeking an office director, Ruina realized he had found a visionary. Waldrop, *op cit.*

[34] The military service R&D organizations initially saw DARPA as a usurper and competitor for scarce research funds. DARPA's efforts over the decades to link with the service R&D organizations and become their collaborator and banker for advanced projects they might not otherwise obtain approval for has helped defuse service hostility, and frequently the collaboration has been highly mutual and beneficial. But resentment remains of DARPA as a favored child, even after a half century. Licklider's efforts mark an early success at cross-stovepipe collaboration, although such success is not uniform.

[35] Licklider, as DARPA's IPTO head, received strong backing from DARPA Directors Jack Ruina and Charles Herzfeld, who bet on his vision, which enabled Licklider to build a cadre of successors – Ivan Sutherland, Bob Taylor and Larry Roberts – who shared and enhanced his vision for a coherent

was able to institutionalize innovation so that successive generations of talent sustained and kept renewing the technology revolution over the long term. At the personal level of innovation, the great groups Licklider started, in turn, shared key features of the Menlo Park, Rad Lab and other groups previously discussed. Licklider's Information Processing Techniques group was the first and greatest success of the DARPA model, but this success was not unique; DARPA was able to achieve similar accomplishments in a series of other technology areas.[36]

One more key point: DARPA has been willing to spawn technology advances not only in the defense sector but in the non-defense economy, recognizing that an economy-wide scale as opposed to a defense sector-only scale may be needed to speed the advance. DARPA has made specific choices to encourage and support technology advances with non-defense organizations, both academic and commercial, rather than defense-only organizations, as its best means of gestating new concepts into implementation.[37] This enables the Department of Defense (DOD) at a later stage to take advantage of this technology evolution speed up, with corresponding shared and therefore reduced development and acquisition costs. This was exactly the case with the IT revolution that Licklider and DARPA made crucial contributions to. Although IT has been in a thirty year development process which is still ongoing, DARPA's support for and reliance on a primarily civilian sector development process enabled DOD to obtain much more quickly and cheaply the tools it needed to solve its initial command and control problem.

Actually, it got far more. When Andy Marshall, DOD's legendary in-house defense theorist and head of its Office of Net Assessment, argued in the late 1980's that that U.S. forces were creating a "Revolution in Military Affairs", [38] this defense transformation was built around many of the IT breakthroughs DARPA initially

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program with ongoing technical process steps that led to the internet and personal computing and a network of related advances. There was no special management doctrine at DARPA that enabled this successive effort but it was allowed by DARPA leaders to proceed full throttle for a decade, until scrutinized somewhat by DARPA Director George Heilmeier. Fluent with practical electronics, he imbedded the "Heilmeier Catechism" which insisted on more application relevance, to Licklider's frustration during his second DARPA tour. Waldrop, *op cit*.

[36] Van Atta, Richard H. et al., IDA, DARPA Technical Accomplishments, Volumes I-V (IDA 1991). See, also, Richard Van Atta, "Fifty Years of Innovaiton and Discovery", in DARPA, 50 Years of Bridging the Gap (April 2008) pp. 20-29. Dr. Van Atta has been generous to the author with his insights on DARPA which are reflected at a number of points in this paper.

[37] Licklider and his colleagues largely relied on universities for idea-creation and the subsequent spin-out of these ideas into new commercial firms (such as Digital or Sun) for their application. While existing smaller commercial firms, such as BB&N, which stood up the internet for DARPA, also played a role, the larger commercial firms, defense contractors and defense R&D organizations were usually not the source of new concepts or their implementation. DARPA thus played an vital role in creating the highly productive pathway in the U.S. late 20th century IT economy of academic-start-up-venture funding-commercialization, and the institutions that grew up to line this pathway.

[38] Andrew Marshall, Memorandum for the Record, "Some Thoughts on Military Revolutions – Second Version" (Aug. 23, 1993); Nicholas Lehman, Dreaming About War, The New Yorker (July 16, 2001) <http://www.comw.org/qdr/0107lemann.html>

sponsored.[39] Admirals Bill Owens and Art Cebrowski, and others, in turn, translated this IT revolution into a working concept of "network centric warfare"[40] which further enabled the U.S. in the past decade to achieve unparalleled dominance in conventional warfare. And the foundation of this IT revolution, that enabled this defense transformation, was a great innovation wave that swept into the U.S. economy in the 90's, creating strong productivity gains and new business models that led to new societal wealth creation[41] which, in turn, provided the funding base for the defense transformation. To summarize, the DARPA model can support traditional technology development within the defense sector where that technology is primarily or overwhelmingly defense-relevant (like stealth). Alternatively it can support joint defense-civilian sector technology development where the technology is relevant to both. This enables DOD potentially to take major advantage of academia's openness to new ideas, the willingness of entrepreneurs to commercialize these innovations, and the corresponding scale of an economy-wide advance.

ELEMENTS IN THE DARPA MODEL

At the Institutional level, DARPA undertakes connected science not simply fundamental research. Its model focuses on revolutionary technology development,

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[39] William Perry and Harold Brown, Defense Department leaders during the Carter Administration, for example, developed what Perry later called an "offsets" theory of defense technology. During the Cold War, the Soviet Union held a roughly three to one advantage in numbers of troops, tanks, and aircraft. Perry has argued that the U.S. at first accepted that disparity because it held an advantage in nuclear weapons. When the Soviets achieved rough parity in nuclear weapons and the missiles to deliver them, U.S. deterrence theory was at risk, so Brown and Perry decided to achieve parity in conventional battle through systematic technological advance. They began a process of translating advances in computing, information technology, and sensors, which had been initiated and long-supported by defense research investments, including DARPA's in particular, into precision weapons at the service level. First exhibited in the Gulf War, these became a massive "force multiplier" for U.S. conventional forces. See, generally, Richard H. Van Atta and Michael Lippitz, Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs, Vol. 1, Overall Assessment (IDA April 2003)(15 years of DARPA reseeach in areas such as Stealth and precisions strike enabled the implementation in the 1990's of the offsets theory of Brown and Perry).

[40] William Owens with Edward Offley, Lifting the Fog of War (JHU Press 2001) Chapt. 3; David Alberts, John Garska and Frederick Stein, Network Centric Warfare (DOD CCRP 1999) <http://www.dodccrp.org/files/Alberts_NCW.pdf>; Arthur Cebrowski and John Garska, Network Centric Warfare, Its Origin and Future, U.S. Naval Institute Proceedings (Jan. 1998). See, generally, Richard O. Hundley, Past Revolutions, Future Transformations: What Can the History of Revolutions in Military Affairs Tell Us About Transforming the US Military (Rand Corp., National Research Institute (1999).

[41] *See for example*, Dale Jorgenson ,U.S. Economic Growth in the Information Age, Issues in Science and Technology (NAS publication, Wash., D.C., Fall 2001 issue) (role of IT drivers in '90's growth).

not simply incremental advance,[42] moving a technology from fundamental science connected through the development up to prototyping stages, then encouraging and promoting its concepts with partners who move it into service procurement and/or the civilian sector for initial production, enabling full innovation not simply invention.

There are other ways DARPA assures connectedness, as suggested above. DARPA developed ability to make technology development connections across the DOD R&D stovepipes by using its funding to leverage contributions from other DOD military service technology development organizations, which in turn promotes service adaptation and procurement of its prototypes. DARPA also uses the other DOD R&D agencies as its administrative agents which, on those days when these stars get aligned, likewise promotes cross-institution collaboration and follow-on procurement.

Other DARPA characteristics enhance its ability to operate at both the Institutional and personal innovation organization levels. The following list, which we will call the twelve commandments, is largely drawn from DARPA's own descriptions of its organizing elements:[43]

- *Small and flexible*: DARPA consists of only 100–150 professionals; some have referred to DARPA as "100 geniuses connected by a travel agent."
- *Flat organization*: DARPA avoids military hierarchy, essentially operating at only two levels to ensure participation.
- *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 organizing R&D efforts. Stated technically, DARPA has "IPA" hiring authoring authority, which gives it the ability to take personnel employed by industry or universities, and it invented "other transactions authority" in contracting which gives it great flexibility and speed in contracting outside the normally lengthy federal procurement process.
- *Eclectic, world-class technical staff* : DARPA seeks great talent, drawn from industry, universities, and government laboratories and R&D centers, mixing disciplines and theoretical and experimental strengths. This talent has been hybridized through joint corporate-academic collaborations.

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[42] Looked at in another way, DARPA historically has had two significant roles, breakthrough military applications and systems, such as stealth or precision strike, and broad generic emerging technologies, such as information processing, microsystems or advanced materials. Both roles interrelate and both have transformational effects. See Richard Van Atta, IDA, Energy and Climate Change Research and the DARPA Model, Presentation to the Washington Roundtable on Science and Public Policy (Nov. 3, 2004) p. 7. DARPA has also developed concept prototypes and demonstrations to meet established military needs which have not yet been defined as military requirements, aside from its breakthrough technology role. Van Atta, *op cit*, Fifty Years of Innovation and Discovery, p. 25-27.

[43] DARPA, DARPA - Bridging the Gap, Powered by Ideas (Feb. 2005); DARPA, DARPA Over The Years (Oct. 27, 2003).

- *Teams and networks*: At its very best, DARPA creates and sustains great teams of researchers that are networked to collaborate and share in the team's advances, so that DARPA operates at the personal, face-to-face level of innovation. It isn't simply about funding research; its program managers are dynamic playwrights and directors.
- *Hiring continuity and change*: DARPA's technical staff are hired or assigned for 3-5 years. Like any strong organization, DARPA mixes experience and change. It retains a base of experienced experts that know their way around DoD, but rotates most of its staff from the outside to ensure fresh thinking and perspectives.
- *Project-based assignments, organized around a challenge model*: DARPA organizes a significant part of its portfolio around specific technology challenges. It works "right-to-left" in the R&D pipeline, forseeing new innovation-based capabilities and then working back to the fundamental breakthroughs that take them there. Although its projects typically last three to five years, major technological challenges may be addressed over much longer time periods, ensuring patient long-term investment on a series of focused steps and keeping teams together for ongoing collaboration.
- *Outsourced support personnel*: DARPA uses technical, contracting and administrative services from other agencies on a temporary basis. This provides DARPA the flexibility to get into and out of a technology field area without the burden of sustaining staff, while building cooperative alliances with the line agencies it works with.
- *Outstanding program managers*: In DARPA's words, "The best DARPA Program Managers have always been freewheeling zealots in pursuit of their goals." The DARPA director's most important job historically has been to recruit highly talented program managers and then empower their creativity to put together great teams around great advances. In particularly fruitful areas, DARPA has created a succession of project leaders that share and build a common vision for progress over time, as in the case of Licklider and his successors.
- *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 historically has focused not on incremental but radical innovation. It emphasizes high-risk investment, moves from fundamental technological advances to development, and then encourages the prototyping and production stages in the armed services or the commercial sector. From an institutional innovation perspective, DARPA is a connected model, crossing the barriers between innovation stages.
- *Mix of connected collaborators*: DARPA typically builds strong teams and networks of collaborators, bringing in a range of technical expertise and applicable disciplines and involving university researchers and technology firms that are often new and small and not significant defense contractors (which generally do not focus

on radical innovation).[44] The aim of DARPA's "hybrid" approach, unique among American R&D agencies, is to ensure strong collaborative "mindshare" on the challenge and the capability to connect fundamentals with applications.

These DARPA "twelve commandments" provide important R&D organizing lessons for any innovation entity, whether in the private or public sectors.

DARPA TODAY – THE FUTURE OF THE MODEL

Economic innovation sectors are best described as ecosystems. Marco Iansati and Roy Levien have argued that within these systems frequently are keystone firms that, like critical species, take on the task of sustaining the whole ecosystem by connecting participants and promoting the progress of the whole system.[45] Iansati and Levien have also argued that these innovation systems start to decline or shift elsewhere when the keystone firms cease being thought leaders and instead shift to what they call "landlord" status. In this state, the "landlord" firm shifts to simply extracting value from the existing system rather than continuously attempting to renew and build the system. There have been concerns voiced in recent years and considered below, that DARPA could be moving away from its keystone role, particularly in IT.

QUESTIONS ABOUT THE DARPA ROLE

DARPA since September 2001 has been increasingly focused on wars in Iraq and Afghanistan, asymmetric conflicts against terrorism requiring different approaches from the symmetric nation state conflict technologies it evolved in the past. While DARPA had been concerned with asymmetric conflicts at least since the demise of the Soviet Union, many noted that the two wars created a significant shift in emphasis at DARPA toward shorter-term military issues and away from some longer-term technology support areas. Concerns about a change in DARPA's role in IT areas, where it has played a keystone role, came up in a series of forums: in a 2005 House Science Committee hearing reviewing DARPA's continuing role in its computer science mission, in a discussion in a Defense Science Board report over its shifting role in microprocessors, in concerns over DARPA's role from PITAC (the President's Information Technology Advisory Council, which was subsequently disbanded by the White House) in IT and cybersecurity, and in papers from a

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[44] There are, of course, exceptions to this, particularly in projects involving systems engineering. Stealth, stand-off precision weapons, and night vision were projects contracted to major defense contractors. Lockheed's Skunk Works has long worked with DARPA as well as the Air Force, and represents a radical innovation model operated within a more standard defense firm.

[45] Marco Iansati and Roy Levien, The Keystone Advantage (Harvard Bus. Sch. Press 2005).

number of IT sector R&D leaders.[46] DARPA has long been famed as the most successful U.S. R&D agency, so these concerns appear worth weighing.

Let's review some of the questions raised about DARPA's future role. Most involve arguments that DARPA has been shifting out of the IT field it played an historic role in creating, even though this technology revolution is still in its youth – after all, we are still not even close to artificial intelligence. DOD's Defense Science Board (DSB) of leading defense technologists issued a report that recognized the critical gains DOD achieved from DARPA's historic role supporting university and industry-led R&D in microprocessor advances. But it concluded that DOD and DARPA were "no longer seriously involved in…research to enable the embedded processing proficiency on which its strategic advantage depends."[47] Since DOD's strategic superiority in symmetric and potentially asymmetric warfare has become in significant part its network centric capability, and secure semiconductor microprocessors are the base technology for this capability, DSB found that DOD faces a serious strategic problem as the newest generation of semiconductor production facilities is increasingly shifting to China and other Asian nations. In fact, the U.S. share of the world's leading-edge semiconductor manufacturing capacity dropped from 36% to 11% in the past 7 years.[48] This problem may be compounded if semiconductor design and research, which historically have had to be co-located with production facilities, shift abroad as well. DARPA's departure from its systematic support of U.S. technology leadership in this field appears to present a serious defense issue if other parts of the Department do not absorb some of this function. DARPA's view in recent years has been that semiconductor advance should be led by industry, increasingly dominated in the U.S. by mature, large-scale firms that DARPA's leaders feel should manage their own problems. But if industry increasingly is being forced to shift abroad because of cost pressure from massive industrial subsidies available there,[49] DOD has a long term problem with what still appears to be a foundation technology. It is serious enough that a 2005 Defense

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[46] House Science Committee Hearing on the Future of Computer Science Research in the U.S., May 12, 2005 (Testimony by Wm. A. Wulf, Pres., National Academy of Engineering, Prof. Thomas F. Leighton, Chief Scientist Akamai Tech. Inc., Joint Statement of the Computing Research Community, and Letters in Response to Committee Questions from W. Wulf and T. Leighton, (July 2005)); Edward D. Lazowska and David Paterson, "An Endless Frontier Postponed", Science, Vol. 308, May 6, 2005, p.757; John Markoff, "Clouds Over 'Blue Sky; Research Agency", New York Times (May 4, 2005) p.12; President's Information Technology Advisory Committee, Report to the President, Cybersecurity: A Crisis of Prioritization" (Feb. 2005); Defense Science Board, High Performance Microchip Supply (Feb. 2005) pp. 87-88. Compare DARPA's responses, House Science Committee Hearing, May 12, 2005 (DARPA Testimony with Appendices A-D).

[47] DSB report, *ibid.*

[48] Norman Augustine, Is America Falling Of the Flat Earth? (NAS Report 2007) p. 17.

[49] Thomas Howell, Competing Programs: Government Support for Microelectronics, in C.W. Wessner, ed., Securing the Future – Regional and National Programs to Support the Semiconductor Industry (NAS 2003); Thomas Howell, et al, China's Emerging Semiconductor Industry (Semiconductor Industry Association Report Oct. 2003).

authorization bill directed DOD to implement DSB's proposals to try to control the problem and retain U.S. technology leadership in this area.[50] A DARPA chip strategy, some would argue, should be to try to secure leadership in a post-silicon, post-Moore's Law world in bio-nano-quantum-molecular computing; DARPA would respond that it is working in a number of those fields. Others would dispute whether it is doing enough to nurture leadership in these emerging areas.

STATUS OF THE HYBRID MODEL

More broadly, DSB notes that one of DARPA's critical roles was to fund through its applied research portfolio (known in DOD as "6.2") "hybridized" university and industry efforts through a process that envisioned revolutionary new capabilities, identified barriers to their realization, focused the best minds in the field on new approaches to overcome those barriers and fostered rapid commercialization and DOD adoption." The hybrid approach bridged the gaps between academic research and industry development, keeping each side knowledgeable about DOD's needs, with each acting a practical prod to spur on the other. DSB expressed concern that this fundamental DARPA approach was breaking down as it cut back its 6.2 university computer science investments, and shifted more of its portfolio to classified "black" research, under pressure from the ongoing war, which cannot include most universities and non-defense tech firms, and, so DSB suggested, reduces DARPA's intellectual mindshare on critical technology issues.[51]

GRID SECURITY

PITAC's report[52] on cybersecurity noted DARPA plans to terminate funding for its High Confidence Software and Systems development area, aiming to curtail cybersecurity funding except for classified work. Historically, one of Eisenhower's key aims in establishing DARPA was to make sure the U.S. was never again subject to a major technology surprise like Sputnik, and it is widely acknowledged that defense and critical private sector IT systems remain vulnerable to cybersecurity attack. Defense theorists, noting the major economic consequences of the 9/11

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[50] Defense Auth. Act for 2005, H.R. 1815 (Sen. Amend. 1361). DOD has established a "trusted foundry" program, initiaed in cooperation with IBM, to try to protect its own access to a stable supply of secure semiconductor chips, a particular concern of intelligence agencies, but this does not assure it long term access to technology leadership in what many continue to argue remains a critical technology.

[51] Total DARPA university funding as a percentage of DARPA science and technology funding fell from 23.7% in FY2000 to 14.6% in FY2004 according to 2005 DARPA data, supplied with hearing testimony, *op cit*, at Footnote 45. A series of major university computer science research department underwent DARPA funding cutbacks of 50% and more in the past six years; some observers have argued that new generations of graduate students are no longer trained in DARPA-hard problems and tied to the agency, so that DARPA has reduced connections to its future talent base.

[52] PITAC report, *op cit*, Footnote 45.

attack on financial markets and the insurance sector have argued that asymmetric cyber attacks on fundamental financial infrastructure by largely unidentifiable state or non-state actors could be devastating to the developed world, potentially striking a powerful blow to the world economy. PITAC has noted that because IT is dominated by the private sector, and even DOD's proposed secure high speed Global Information Grid must interact with the internet, shared solutions between defense and private sectors must be developed, so classified research in many cases cannot be effectively implemented. PITAC identified ten defense-critical IT research areas, from authentication technologies to holistic security systems, it believes require future DARPA investment.

ALTERING THE ECOSYSTEM

Dr. Thomas Leighton, Chief Scientist of Akamai Corp., in response to questions from the House Science Committee, argued that DARPA's most important contribution to IT has been, "its unique approach (and commitment) to developing communities of researchers in both industry and academia" focused on "'pushing the envelop' of computer science."[53] Although DARPA continues to look at some IT problems, "its growing failure to support the university elements of that community is altering the innovation ecosystem" that it created "in an increasing negative way, with no other agency ready or able to pick up that role." Some university computer science departments and labs report that although the DARPA cutbacks in funding have been at least partially made up by industry support, this is often short term and not breakthrough-oriented, and often is from Asian firms that control the IP for technology developed and for obvious competitive reasons preclude it going into U.S. spinoffs. It should be noted that an increase in NSF computer science funding has offset some of the effects of the decline in DARPA university funding. DARPA's leadership has argued, as justification for the cutback, that it was not seeing enough new ideas from this sector.

Dr. William Wulf, a computer scientist and until recently President of the National Academy of Engineering, told the House Science Committee that, "There is now no DOD organization like the 'old DARPA'…that fills the role of discovery of breakthrough technologies."[54] Although he acknowledged that DARPA was looking at cognitive computing, he argued that there were problems in the subjects DARPA was selecting for IT research because it was not confronting key security areas. For example, "our basic model of computer security (perimeter security) is fatally flawed" and will not be solved by the "short term, risk-adverse approach being currently taken by DARPA." He argued that our "ability to produce reliable,

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[53] Response of Dr. Tom Leighton to Questions from the House Science Comm., July 7, 2005, *op cit*, Footnote 45.

[54] Dr. William A. Wulf, Response to Questions from the House Science Comm., July 2005, *op cit*, Footnote 45.

effective software" is tottering on "the brink of disaster" but DARPA has not focused on solutions, and also is not reviewing the fact that our basic model for computing is not yet close to human brain capability, and requires a new model "of parallel computing" with "architectures and algorithms of immense power." He also argued that the "use of computers in education has progressed little from the 'automated drill' model of the Plato system of the 1960's" although "we know much more about how people learn physiologically and psychologically" including how "emotion interacts with learning" which we could put to good use in quickly training troops in urban combat and counterinsurgency, and DARPA should also be more involved in this area. DARPA spokesmen have noted in response to these arguments that DARPA has funded, as has the Army, soldier training simulation systems at USC's center for this work, and that it was the primary initial funder of grid computing. Perhaps one part of the answer is that DARPA may lack a Licklider with the vision to see and evolve a new IT territory. Critics respond that that because of a top-down management style in recent years at DARPA, office directors and program managers lack the authority to initiate in this way.

It is generally understood that DARPA has had to be increasingly focused on solving a problem it ran into at the end of the Cold War with its resulting cuts in defense procurement starting in 1986: the breakdown of technology transition from DARPA into services. DARPA even during the Cold War had a transition problem with the services as it focused on disruptive, change-state, radical innovation. It solved some of these problems in the past by transitioning technology, such as IT, into the civilian economy, In other areas, it had to rely on the clout of the Secretary of Defense and, when available, a strong Director of Defense Research &Engineering (DDR&E). DARPA typically did not enjoy a concensus with the military unless it was hammered out by the Office of the Secretary of Defense and the service secretaries. Nonetheless, following the Cold War, technology transition declined. Unsuccessful in building a new consensus with the military services for transferring the results of revolutionary technology investment into service procurement, DARPA technology strategy has been moving from its history of radical innovation to more incremental innovation, shifting a larger part of its investment into later stage development efforts that the services are more ready to invest in. Defense budget analysts report that shorter term incremental work, space launch, and satellite "repair" are requiring growing parts of the DARPA budget. A new DARPA review process, mandated by improving transition to the services, of frequent "up or out" decisions with limited development time is placing more of its R&D on a shorter term course. Congress may be playing a role in this, as well, focusing more on DARPA's record rather than it's overall impact. The current emphasis on a pre-agreed transition plan may further limit disruptive work. Some believe that resulting more frequent policy reversals and turns may limit DARPA's ability to mount enough creative, longer-term investment programs so important to past development. Although the heart of DARPA's creativity in the past was in highly talented and empowered project managers, some believe that the role of project managers has been significantly limited by this short term review approach. Although DARPA has always been able to pick among the brightest technologists in the nation, its larger focus on classified programs[55] may limit its access to some of the university researchers it has relied on in the past, creating difficulty over time in attracting talent.

DARPA in the past has operated in both the civilian and defense economies, understanding they are the same economy. As noted, it has built "great groups" and spun off civilian-relevant technology, such as in computing, to the civilian sector where it evolved further, enabling DOD to buy it back at radically lower costs and to take advantage of civilian development advances. Alternatively, it has spun off to the defense sector defense-only technologies like stealth and unmanned aerial vehicles (UAV's). DARPA's need to focus on the current asymmetric conflict and corresponding classified work, as well as shorter term technology transition, may make it less able to spin off technology to the civilian economy, despite DOD's growing capital plant cost crisis and its need to take better advantage of advances in that sector.[56] Given DARPA's historic role in successfully straddling both sectors, DARPA's needs to protect its ability to play in both worlds.

Much of the above debate is driven by IT sector concerns. But there is a larger debate emerging over DARPA's role in IT. Because DARPA, starting with Licklider, played a profound role at the center of most aspects of the IT revolution, there is a question whether its current focus on shorter term and classified programs due to the war inevitably will signal a broader retreat from this sector[57] and does the state of the sector justify such a retreat?[58]

The first question that must be asked is where are we in the IT revolution? In the past, innovation waves fully matured in 40 or 50 years and society moved on to the next innovation stage. Accordingly, some argue that the IT revolution is maturing and that we need to move on to the next big things.[59] Where do we measure the IT wave from? If we measure it from the first post-World War II mainframe, ENIAC, the half century mark for the revolution ran out in 1995. 1995, however, was the period when we were bringing on personal computing and internet

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[55] DARPA has always had, of course, a large classified program base separate from its academic research. The assertion here is that the balance has changed with more of a tilt toward classified work.

[56] Research investment also affects defense capability. With defense R&D, nations generally "get what they pay for", with weapon system capability and quality directly corresponding to intensity of research investment. Andrew Middleton and Steven Bowns, with Keith Hartley and James Reid, The Effect of Defense R&D on Military Equipment Quality, Defense and Peace Economics, Vol. 17(2) (April 2006), pp. 117-139.

[57] Vernon Ruttan has raised the concern that with the post-Cold War decline in defense innovation, the U.S. innovation system may not now be strong enough to launch new breakthrough technologies in either the public or the private sector. Vernon W. Ruttan, Will Government Programs Spur the Next Breakthrough? Issues in Sci Tech (Winter, 2006).

[58] *Op cit*, Footnote 45.

[59] Robert Atkinson, "Is the Next Economy Taking Shape?" Issues in Science and Technology (Winter 2006) p. 62.

access at levels that reached a major portion of our society. If we measure the IT innovation wave from around 1995, when real time and networked computing took off with the public, then we are still a decade into an IT revolution wave. Perhaps DARPA should be moving on to another innovation wave?

On the other hand, the IT revolution may be different from steam engines or electricity. The four- or five-decade model for past innovation waves may not be fully relevant to the IT revolution. When we work with the information domain, we have to keep in mind that we are working with a fundamental force that Norbert Weiner suggested in 1948 was a coequal to mass and energy.[60] We have already been through a succession of unfolding and sometimes parallel IT waves, from business (and military) computational capability, to data retrieval, processing and display, to advanced digital communications, to data mining and using mass data as a predictive tool, and we are beginning to make progress on symbolic manipulation and computer theorem proving and are thinking about quantum computing. The grail quest of computing is true artificial intelligence. This is not a technology pursuit similar to past efforts because it is ultimately a quest to take on a godlike power.[61] We have a long, long way to go in achieving this stage. Progress on the Turing Test -- can a computer's thinking be mistaken for a human's - has been limited.[62] Although computers now play chess at the highest level and drive SUVs through DARPA's desert and urban obstacle courses, computing isn't even close yet to the intuitive powers of the human brain. Although an artificial intelligence quest may ultimately be futile or only partially achievable, even if we have to settle for Licklider's "Man-Machine Symbiosis" we have a long way to go before this more limited vision is close to being played out. In other words, there may be decades of radical, breakthrough innovation to go in IT, not simply incremental advances. If this is right then DARPA, given its historic breakthrough technology mission and responsibility to avoid Sputnik-like technology surprises, continues to have a future in IT.

Even setting aside the ultimate artificial intelligence challenge, Victor Zue has argued that the next generation of computing challenges are more profound than ever.[63] While yesterday's problem was computation of static functions in a static environment within well-understood specification, today, adaptive systems are needed that operate in environments that are dynamic and uncertain. While computation was the main past goal, communication, sensing and control are also now critical. While computing used to focus on the single operating agent, it must now focus on multiple agents that may be cooperative, neutral or adversarial. While batch processing of text and homogeneous data used to be the task, stream

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[60] Norbert Wiener, Cybernetics or Control and Communication in the Animal and the Machine (Hermann et Cie, Paris and MIT Press, Cambridge, Mass. 1948).

[61] Ann Foerst, God in the Machine (Penguin Books 2005)

[62] Mark Halpern, The Trouble with the Turing Test, The New Atlantis, No. 11, Winter 2006, pp. 42-63.

[63] Victor Zue, Introduction to CSAIL (MIT April 15, 2008) pp. 6, 14.

processing of massive heterogeneous data now is. While stand-alone applications once prevailed, deep interaction with humans is now key. While there was a binary notion of correctness in computing, now there is a trade-off between multiple criteria. In today's computing world these opportunities arise in a far more complex environment of cheap communication, ubiquitous communication, overwhelming data, and limited human resources. Major IT tasks for the military become, for example, much deeper human computer interface, social and cultural modeling; far more robust and secure computation; smart, self-directed autonomous surveillance; and robots ready for human interaction.

DARPA strongly maintains it is funding IT, even though an increasing amount of its work must be classified. It is also funding what it believes is a critical breakthrough area in computing, cognitive computing, and supports bio computing and robotics. The ongoing wars in Iraq and Afghanistan appropriately force DARPA toward shorter term solutions for the military; it went through a similar evolution during the Vietnam War. DARPA has had, as noted, a profound problem with technology transition with the military services and to solve it, must focus on better meeting service needs. Still, the question must be asked whether there is a danger that DARPA may be over time retreating into Iansati's and Levien's "landlordism" – not continuously renewing but living off incremental improvements on past advances. For example, it is felt by some observers that DARPA lacks a tactical technology vision as that program has become increasingly smaller-scale, less coherent and non-tactical. DARPA should also evaluate the emerging new dimensions of whether it has a coherent IT vision for approaching some of the challenges Zue and others suggest. Given DARPA's unique historical role in U.S. technology advance,[64] this is a significant issue. Because even great technology advances take a decade or two to produce, the pipeline of advance is hard to see, but problems we may have now in filling that pipeline will have a profound effect on our future a decade or more out.

DARPA is not the only aspect of DOD technology leadership facing difficulties. DOD depends on a strong fundamental physical science research to support its breakthrough potential, but these programs and funding levels are in decline.[65] Boomer generation scientists have been the mainstay of DOD science talent in its labs and research centers, but are now retiring in droves, and are not being adequately replaced. DOD faces a very serious science talent supply problem and needs hiring and retention flexibility beyond civil service limits, but a rigid position in the past by DOD personnel staff that there must be only one personnel system for all at DOD has thwarted Congressional reform efforts to create more

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[64] Van Atta, Richard H. et al., *op cit,* IDA, DARPA Technical Accomplishments, Volumes I-V (IDA 1991).

[65] James A. Lewis, Waiting for Sputnik (CSIS March 1, 2006). See, also, John Young, Director of Defense Research and Engineering, Info Memo for Secretary of Defense Robert M. Gates, DOD Science and Technology Program (Aug. 24, 2007) (need and corresponding proposal for increased DOD S&T funding, listing potential high pay-off research areas).

flexibility for scientists. The pressure of the tempo of ongoing military operations is, in turn, putting pressure on funding for science in the military services. The pattern of technology leadership in DOD may not be as strong as in the past. DDR&E leaders of the caliber of John Foster, Malcolm Currie and William Perry have been infrequent, and the overall depth of technical competence in the Office of the Secretary of Defense to backup DARPA and push for technology implementation has declined. Overall, the picture for DOD science is not getting prettier, and this is against a backdrop of serious problems in U.S. physical science in general, as explored in recent major reports by the National Academies.[66]

Yet our security challenges are growing. The emergence of the terrorist model, of non-state actors relatively immune to state-to-state pressure, represents a profound asymmetric challenge to a Western military model that has been world-dominant since the 15th century. In parallel is the emergence of other peer competitors, working on both symmetric and asymmetric approaches, pursuing a technology innovation model for economic development which, as discussed, has significant military implications. This raises a fundamental concern: can U.S. technological superiority be the continuing basis of U.S. security in an increasingly globalized technological and economic world? Since U.S. economic and military success, as argued at the outset, has relied on profound integration between defense and civilian elements of its innovation system for technological superiority both military and economic, consequences on one side of this equation, such as long term DARPA capability, have major effects on the other side.

SUMMARY

Arguably innovation organization – the way in which the direct innovation factors of R&D and talent come together, how R&D and talent are joined in an innovation system – is a third direct innovation factor. DARPA emerged as a unique model – operating at both the institutional and personal level of science organization. Building on the Rad Lab example, it built a deeply collaborative, flat, close-knit, talented, participatory, flexible system, oriented to breakthrough radical innovation. It has used a challenge model for R&D, moving from fundamental, back and forth with applied, creating connected science linking research, development, and prototyping, with access to initial production. In other words, it followed an innovation path not simply a discovery or invention path.

Like all human institutions, these organizational models are transitory.
The DARPA model has been one of the longest lasting, unique in the federal government, and seemed to be the most capable of ongoing renewal.

But that DARPA model now may be shifting under pressure of ongoing operations, particularly regarding DARPA's role in the IT sector, with potential long

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[66] NAS, Rising Above the Gathering Storm (2007 ed,); NAS/Augustine, Is America Falling Off the Flat Earth, *op cit.*

term effects on U.S. defense as well as civilian sector technology superiority. This shift occurs against a backdrop of overall problems in U.S. physical science strength. DARPA has long served a keystone function in the U.S. innovation system and it is in the nation's national security and economic interest that it continue to avoid "landlord" status.