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The Role of DARPA in Seeding and Encouraging New Technology Trajectories: Pre- and Post-Tony Tether in the New Innovation Ecosystem

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This paper, a case study of the Defense Advanced Research Projects Agency (DARPA), sheds new insights into the role of the U.S. State in innovation. The study uses grounded theory-building methods to unpack the processes by which DARPA fosters new technology trajectories within the institutional ecosystem supporting the computing industry. At the heart of the paper are 50 in-depth field interviews of DARPA program managers and related microsystems technologists within start-ups, universities, government institutions, and the five established computing firms. Going further, the paper triangulates this qualitative interview data with participant observation, archival data, and bibliometric data to provide a holistic view of the forces driving technological change. The results find DARPA to be a uniquely adaptive organization. Yet, throughout such adaptations, DARPA program managers use the same five-step process to influence technology. With its latest shift, DARPA may be effectively (1) narrowing the valley of death, (2) coordinating innovation within a vertically fragmented industry, and (3) influencing innovation to serve military needs despite primary demand being in commercial applications. This "new DARPA" may, however, leave the U.S. technology pipeline without new sources.

Keywords: DARPA, State, Innovation, Social network, Computer

DRAFT – PLEASE DO NOT CITE WITHOUT PERMISSION OF THE AUTHOR

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Are you familiar with the allegory of the cave? (Plato, The Republic*) … it's the same thing (with trying to deduce technology directions from) funding. The technology direction is a separate thing.*

– Lead technologist, Government Lab.

1. Introduction

With more and more jobs moving overseas, there has been rising concern over the ability of the U.S. to remain competitive in the global economy. In 2006, a committee from the National Academy of Sciences found a common "disturbing picture" across a multitude of industries, specifically, "a recurring pattern of abundant short-term thinking and insufficient long-term investment." Key among their recommendations was to "strengthen the nation's traditional commitment to long-term basic research that has the potential to maintain… the flow of new ideas that fuel the economy"(NationalAcademies, 2006).

The committee's recommendations are not surprising. In the earlier part of the 20th century, much R&D was still housed within corporate laboratories such as Bell Laboratories, GE Research, and Xerox Parc. In the 80s and 90s, with the rise of industrial clusters around Rt. 128 and Silicon Valley, research emerged suggesting key advantages to networked small and medium sized enterprises. Such enterprises were shown to be able to react more quickly to changing business environments, and to be more innovative than their larger, slower-moving counterparts (Piore and Sabel, 1984; Pavitt and Townsend, 1987; Powell, 1990). Today, many large firms outsource their innovation needs to universities and small firms through technology alliances and acquisitions (Cohen and Levinthal, 1990; Lamb and Spekman, 1997; Chesbrough, 2003).

This industrial model may have disadvantages for long-term innovation. Although often more flexible and innovative, small and medium sized firms also have fewer resources. With skills in China and India improving, firms can now manufacture offshore early in the innovation process. Recent research suggests that with high cost pressures, such firms may have incentives to produce low-tech products offshore rather than to invest in innovations critical to long-term markets (Fuchs, 2005). Additional studies have demonstrated challenges in this new environment in the alignment of firm incentives (Casadesus-Masanell and Yoffie), in coordination across firms (Gawer and Cusumano, 2002; Iansiti and Levien, 2004), and in supporting long-term research (Macher et al., 2000). Thus, while individual firms' decisions in this environment may be optimal for their short-term survival, the consequences for the broader innovation ecosystem and for U.S. long-term innovation remain uncertain. Understanding to what extent and in what form government policies may be necessary to support long-term innovation in this new environment may be critical to maintaining national competitiveness.

To shed insights into this question, this study focuses on the Defense Advance Research Projects Association (DARPA) – a pioneer of the methods used by the U.S. developmental network state (Block, 2007) and one of the agencies to achieve some of the most striking early successes in technology development (NRC, 1999). Several factors make today a particularly interesting time to study DARPA. First, while DARPA has historically enjoyed significant success in introducing and commercializing new technologies, DARPA has under the directorship of Tony Tether (2001-present) undergone momentous changes. These changes have faced significant criticism from the academic computing community (JointStatement, 2005;

Lazowska and Patterson, 2005). Given the recent shift of DARPA funding away from academia to established industry vendors, (Markoff, 2005) this criticism is not surprising. Second, leading up to this shift within DARPA, there have been significant changes in the industry structure, market structure, and R&D structure in computing. It is unclear whether the changes within DARPA are a necessary adjustment to changes in the computing industry and its innovation ecosystem. Finally, in the last decade a wealth of organizations have sprung up copying DARPA and aimed at technology development for other communities, outside the Department of Defense. The most obvious examples include Advanced Research and Development Activity (ARDA, 1998) -- later renamed the Disruptive Technology Office (DTO) -- for the intelligence community; HSARPA (2002) for homeland security; IARPA (2006) again for the intelligence community, and into which the DTO's activities were folded; and ARPA-E (2007) which although it has not yet received funding in the U.S. budget, is meant for the Department of Energy. With the recent development of these organizations, it seems important to step back and look at the processes by which DARPA, historically, has encouraged new technology developments; what, over the years, about DARPA has changed and what has remained constant; and, most importantly, how these processes are working in today's innovation ecosystem.

The results of this study suggest three main findings: First, DARPA's ability to change with changing political, environmental, and technical times is a critical strategic asset enabled by the structure of the organization. Second, regardless of organizational changes in DARPA, DARPA program managers continue to use five processes to seed and encourage new technology trajectories with the academic and industrial communities. This processes consists of (1) facilitating conversations among similar researchers by bringing them together to brainstorm on technology directions, (2) gathering momentum around key ideas by providing seed funding to disparate researchers working on similar projects, (3) disseminating knowledge and creating community by bringing funded researchers together in research workshops to discuss their results, and (4) acting as third party validation of new technology directions to latter-stage funding agencies (like NSF) and to industry, and (5) not sustaining the technology. Third, although the focus of DARPA's efforts over the past seven years have shifted from universities to collaborations across universities, government labs, and industry, and despite significant criticism from the academic community, DARPA may be doing a good job at (1) narrowing the valley of death, (2) coordinating innovation within a vertically fragmented industry, and (3) influencing technology development to still serve military needs despite primary demand for computing having moved into commercial applications. Finally, despite these potential strengths of the recent shifts within DARPA in the current innovation ecosystem, in focusing on "bridging the gap" from invention to innovation, DARPA may have left the technology pipeline without new sources of innovation.

2. Previous Research: Networks of Innovators and the Role for the State

2.1. Changes in the U.S. Innovation Ecosystem: Networks of Innovators

Today, complex networks of firms, universities, and government labs are critical features of many industries, especially in fields with rapid technological progress, such as computers, semiconductors, pharmaceuticals, and biotechnology (Powell and Grodal, 2005). This complex ecosystem of innovators has only become commonplace over the past two decades (Powell and Grodal, 2005). A National Research Council assessment of eleven US-based industries observes in every sector an increased reliance on external sources of R&D, notably universities, consortia, and government labs, and greater collaboration with domestic and foreign competitors, as well as customers in the development of new products and processes (Mowery, 1999). The National Science Foundation data show a marked increase by the mid-1990s in the formation rates for international alliances linking US firms with their domestic competitors. These collaborations were motivated largely by concerns with the development of new technologies. There are also growing links between US firms and universities, and greater involvement by firms and government labs in research joint ventures. As a consequence, (Mowery, 1999) observes, "the diversity of institutional actors and relationships in the industrial innovation process has increased considerably."

With increased linkages and diversity of institutional actors in industrial innovation, there has been growing interest in how technology directions evolve and are coordinated across these institutional boundaries. At the firm level, driving this need for coordination has been the increasing vertical disintegration and fragmentation of production (Gereffi et al., 2005). In response, the business strategy literature has begun exploring firm ecosystems and the technological interdependencies among firms (Moore, 1996; Iansiti and Levien, 2004; Adner, 2006). This ecosystem construct raises a new set of issues for both researchers and managers to consider. Such issues include joint development incentives (Casadesus-Masanell and Yoffie, 2005), options for positional leadership and coordination (Gawer and Cusumano, 2002; Iansiti and Levien, 2004), the timing of resource commitments (Almeida et al., 2006), the recalibration of customer expectations (Adner, 2006; Tripsas, 2006), and the evolution of industry architectures (Jabcobides, 2005). Research to-date has explored the challenges that arise when incentives across the ecosystem are not aligned (Casadesus-Masanell and Yoffie, 2005), the role of ecosystem partners in shaping firm's abilities and incentives to compete for different market segments (Christensen and Rosenbloom, 1995), and the activities that focal firms undertake to induce partners to favor their specific technology platforms (Gawer and Cusumano, 2002). Research has also explored when alliances promote increased interfirm knowledge transfers versus specialization (Macher and Mowery, 2004). The business strategy literature, however, has failed to explore the role, if any, government may need to play in addressing coordination problems and market failures within this. Particularly at risk within this vertically fragmented ecosystem may be long-term technology development incentives (Macher et al., 2000).

The answer to this cross-firm coordination challenge may in part come from a second literature on technological change – the literature on individual social networks (in contrast to the above literature on networks of firms). While the business strategy literature has focused on the technological interdependencies among firms and how firms evolve technological platforms, the emerging literature on networks of innovators has focused on individuals and how their interpersonal networks influence technology trajectories. This research has explored how inter-organizational networks and communities socially construct technology cycles; and, in reverse, how technological outcomes determine the evolution of these organizations and communities (Van de Ven and Garud, 1989; Powell, 1990; Nelson, 1994; Van de Ven and Garud, 1994; Bijker, 1995; Rosenkopf and Tushman, 1998). According to this literature, knowledge flows within social networks are influenced (1) by the type of ties – strong versus weak (Granovetter, 1973); (2) by the type of knowledge flowing across those ties – tacit (Nonaka, 1991) versus codified (Zander and Kogut, 1995), standardization, stickiness (VonHippel, 1994), ambiguity (Szulanski, 1996), and complexity (Hansen, 1999; Sorenson et al., 2006); (3) by the type of node, (4) by the relational proximity between nodes – including common identity and language, similarities between scientists (Song et al., 2003), and communities of practice (Brown 1991);

(5) by geographic proximity (Allen, 1977; Teece, 1977; Mansfield et al., 1982; Saxenian, 1994; Porter, 2001); and (6) by labor markets (Azoulay, 2003).[1]

The social networks which influence technological change can be both formal and informal. Formal social networks can include, task forces (Rosenkopf and Tushman, 1998), standards bodies (Miller 1995; West 2000), and roadmapping institutions (Kappel, 2001). Informal knowledge-sharing and alliances have been shown to occur among engineers in close geographic proximity (Allen, 1977), among engineers within the same region (Saxenian, 1994) as well as among engineers within rival firms (Allen, 1983; VonHippel, 1987). Regardless of whether this information sharing is occurring within formal task forces or informally over beers, research has discussed in the previous paragraph, social networks can lead knowledge at times to flow more-easily between people across firm boundaries, than people within the boundaries of a single firm.

Despite the significance of individual social networks in influencing innovation, little is understood about the role, if any, of the state within this social framework, and how this social framework may interact within the broader firm and ecosystem incentives to enable the coordination of technological change.

2.2. Industrial Policy in the United States

Debates on the appropriate role for the state in science and technology development are as real today as they were 232 years ago, when Adam Smith first wrote about the invisible hand in the *Wealth of Nations* (Smith, 1776). Today, authors continue to promote the benefits of free markets, from Milton and Friedman's Free to Choose (Friedman and Friedmand, 1980), which argues against the need for the National Science Foundation, to Arora and Alfonso's *Market's For Technology* (Arora et al., 2001), which suggests that a combination of patent law and the vertical fragmentation of firm boundaries enables a free market for ideas. Despite this free market ideology, there is a long history of the U.S. government using innovation and industrial policies to help ensure technological upgrading and the transfer of inventions into commercial products (Block, 2007). In his classic history of U.S. industrial policy, Graham argues that a leading problem with the U.S. government's developmental policies have been their lack of coordination (Graham, 1992). He notes that under Keynesian thought, "economic policy meant manipulating spending and taxation, money, and credit. The government's function was to influence the *volume*, not the *direction*, of investment" (Graham, 1992) Block argues that this lack of an explicit developmental policy – defined here as a policy of the government picking technology winners – in the U.S. is due to market fundamentalism forcing existing developmental initiatives to remain largely hidden from public discussion (Block, 2007). Recently, however, Atkinson and Wial have attempted to start a public discussion, echoing Graham in their call for a National Innovation Foundation to coordinate the activities of the fragmented technology development organizations in the United States (Atkinson and Wial, 2008). Also bringing the potential role of the U.S. State in choosing technology winner into recent public discussion, Office of Science and Technology Policy in their report, "The Science of Science Policy: A Federal Research Roadmap," call for metrics and better modeling techniques to help U.S. bureaucrats in making technical investments (Valdez and Lane, 2008). Recent research, however, suggests that rather than central coordination or better-tooled bureaucrats, there may be another alternative to better-informed science and technology investment, with existing examples already functioning quite well within the United States. This

[1] For a review of the literature which suggests many of the above categories see (Argote, McEvily, Reagans 2003).

alternative is the Developmental Network State.

Developmental policies have recently been broken into two categories – the Developmental Bureaucratic State and the Developmental Network State (O'Riain, 2004; Block, 2007). The Developmental Bureaucratic State typically uses top-down polices involving government-based research and firm subsidies to develop local expertise in targeted industries, and help firms invest in upgrading (Kim, 1997; Amsden, 2001; Breznitz, 2007). The most prominent Developmental Bureaucratic States are developing countries. As skills develop, these countries move from policies promoting imitation to promoting local innovation. While a centralized developmental state is feasible in developing countries, this role becomes more difficult when there is no international leader that firms can imitate, and uncertainty as to what will be the long-term technological winners is high (Block, 2007) Many developed countries – in particular the U.S. and Western Europe – instead have a Developmental Network State. In contrast to the Developmental Bureaucratic State, the Developmental Network State involves public sector officials working closely with firms to identify and support the most promising avenues for innovation (Block, 2007). These public sector officials, in promoting innovation, execute four overlapping tasks – providing resources to target areas, opening windows for scientists and engineers to bring and receive support for new ideas, brokering – i.e. connecting different groups (both technologist-to-technologist and technologist-to-business) so they can take advantage of each other's knowledge, and facilitation – i.e. creating standards, infrastructure, and regulation to ease the introduction of the new technology. To successfully execute these tasks, the public officials must be deeply rooted in the technological community they are funding, and have the embedded autonomy to act on their knowledge (Block, 2007). This networked nature of the DNS is particularly significant given the increased vertical disintegration of innovative activities and increased linkages across organization-types and researchers involved in innovative activities in recent years in the United States. The embedded autonomy of the Developmental Network State bureaucrats is critical to the State maintaining flexibility to changing technical, political, and economic times. The existing literature on the Developmental Network State, however, is primarily theoretical (the empirical work is on Ireland), and leaves little insights into how an organization which is part of a Developmental Network State might be formulated and what processes this organization's bureaucrats should use to successfully gain momentum around new technology directions. This paper focuses on the pioneer of the U.S. Developmental Network State – DARPA.

3. Organizational Background: The Changing Faces of DARPA

"The only constant is change." Laertius, Diogenes. *Lives of the Philsophers*.

An often overlooked asset of DARPA as an organization is its ability to shift with the political and economic environment of the times. This paper brings a magnifying glass to on one such shift within DARPA's history – DARPA's shift from a focus on U.S. international competitiveness under directors Gary Denman, Larry Lynn, and Frank Fernandez in the 1990s, to a focus on "bridging the gap" between nascent ideas and commercial (military or industrial) application. This shift, which was led by DARPA's 18th director, Tony Tether (2001-2008), has drawn significant criticism, from both academic and industrial communities in computing as a move which abandons the "old DARPA." Looking at DARPA's history, however, it is unclear precisely what that "old DARPA" might be. As can be seen in Table 1, the political and

Table 1: The Changing Face of DARPA: A Historical Chronology of the Organization

Decade	1958	1960s	1970s	1980s	1990s	2000s
Name	ARPA ('58-72)		DARPA ('72-93)		ARPA ('93-96)	DARPA ('96-08)
Era		Basic Research	Military Missions	Industry Focus	Competitiveness, Internationalization	Industry to Military
President	Eisenhower ('53-61)	Eisenhower ('53-61) Kennedy ('61-63) Johnson ('63-69)	Nixon ('69-74) Ford ('74-77) Carter ('77-81)	Reagan ('81-89)	Bush ('89-93) Clinton ('93-01)	Bush Jr. ('01-08)
Legislative/ Political Environment	Cold War Sputnik ('57)	Cold War Vietnam War ('59-75)	Cold War Vietnam War ('59-75) Mansfield Act ('69)	Cold War Ends Star Wars Noyce -more VC ('78) Concern about competitiveness against Japan; National Cooperative Research Act ('84)	Field forced to leave due to excessive industrial focus ('90); Sematech desires internationalization, weans from public assistance ('95); DARPA criticized for slow transition to military ('97); Increased inter-organizational and international R&D linkages	World Trade Center Attacked (Sept. 11, 2001); Bush Jr. enters Iraq ('03); Increased concerns about U.S. competitiveness, especially against India, China (Rising Above the Gathering Storm 2005); Criticism of DARPA for not funding basic R&D (Lazowski House Statement 2005)
DARPA Directors	Johnson ('58-60)	Betts ('60-61) Ruina ('61-63) Sproull ('63-65) Herzfeld ('65-67) Rechtin ('67-70)	Lukasik ('70-75) Heilmeir ('75-77) Fossum ('77-81)	Cooper ('81-85) Duncan ('85-88) Colladay ('88-89) Fields ('89-90)	Reis ('90-92) Denman ('92-95) Lynn ('95-98) Fernandez ('98-01)	Tether ('01-08)
DARPA Environment	Supercede inter-service rivalry; prevent technological surprises	Scientific merit over military; focus on best people - independence, intellectual quality	Mid-term exams, deliverables, success measures	Strategic computing initiative ('83); Sematech ('87); pyramid of technologies; connecting academia and industry	Fernandez priorities: people, competition, outreach, experimentation ('98)	Phases, milestones, accountability; "Transforming Fantasy" (01-03); "Bridging the Gap" ('03-'08)

international environment surrounding DARPA have throughout its history been strong determinants of DARPA's focus and its execution of its mission. (For a detailed discussion, see Appendix 1.) Further, while the computing industry's structure and technological maturity are undeniably different today than they were in the past, many themes repeat themselves. For example, there are notable parallels between Tether's period and leadership and that of George Heilmeier in the 1970s. The paragraphs which follow detail the most recent shift within DARPA, first by describing the political and economic environment and DARPA leadership from 1992-2001, and then by describing the period from 2001-2008.

In 1992, Former Secretary of Defense Richard Cheney announced "a new, post-Cold War DoD strategy of spending less on procurement of new military systems, while maintaining funding for R&D to develop new technologies for building future systems and for upgrading existing systems"(OTA, 1993). This statement proved to be representative of (D)ARPA during the 1990s. During the period from 1992-2001 DARPA was led by three directors – Gary Denman (1992 – 1995), Larry Lynn (1995 –1998), and Frank Fernandez (1998-2001). While Gary Denman was appointed under President George H.W. Bush, he continued to serve as director for another two years under President William Clinton, who took office on January 20, 1993. In their 1993 assessment, the OTA writes, "Early stages of R&D, in which ARPA is most heavily involved (basic research through technology demonstration), will probably be least affected by reductions in defense spending" (following the cold war.) They continue, "Furthermore, based on military interests alone, ARPA will probably become more involved in the development of dual-use technologies. Despite the apparent divergence of military and commercial systems, many component technologies from which these systems are constructed continue to converge" (OTA, 1993). It was also in 1993, during Denman's tenure, that DARPA briefly dropped its "D" and returned to it's original name of ARPA.

Following Denman, Larry Lynn and Frank Fernandez were both subsequently appointed by President Clinton. Both Lynn and Fernandez continued the focus within (D)ARPA on basic research. In an article on the ingredients of military innovation and transformation, written by Lynn after he retired from DARPA, Lynn notes that an often-used criterion within DARPA when evaluating the probability of technical and operational success of a project was "If you succeed in all your goals, will it make a real difference?" (Lynn, 2003). Lynn was also part of DARPA's first inclusion of basic biology research into DARPA's budget (Marshall, 1997). Fernandez, in turn, focused on quality and independence in a manner reminiscent of ARPA's second director, Ruina. In his March 2000 statement to the Senate, Fernandez states that he has four priorities. Starting with what he believes to be the most important, he states that these are "to attract top-quality people; to foster an atmosphere of healthy competition for top performers; to reach outside the normal DoD industrial base for ideas; and to work with the Services and the Unified Commands to use experimentation as a vehicle to provide the iteration between operational concept and technology development that I feel is necessary to achieve revolutionary innovation in war fighting" (Fernandez, 2000).

On January 20, 2001, George W. Bush took office as the 43rd President of the United States, and on June 18, 2001, Tony Tether was appointed as the new Director to head DARPA. Prior to becoming the director of DARPA, Tether had steadily risen in his career through a combination of military and industrial positions. Having served for four years as the DOD's national intelligence (1978-1982), he came to the position of DARPA director under a directive from Secretary of Defense Donald Rumsfeld that the new director must make DARPA an entrepreneurial hotbed that will give the U.S. military the tools it will need to maintain the nation's access to space and to protect satellites in orbit from attack (Rensselaer, 2002).

By the time of Tether's appointment, much had already changed in the innovation landscape and the computing industry landscape within which DARPA acted. Within months, however, of Tether's appointment, many aspects of the political landscape in the U.S. also began to change. Less than three month after Tether was appointed, two hijacked planes were flown into the World Trade Center in New York City on September 11, 2001. Still, the theme of DARPATech 2002 remained "Transforming Fantasy," and Tether's introduction speech at that time, while it mentions "transitioning" technology and milestones, still has significant focus on people and looking far out into the future (Tether, 2002). On October 16, 2002, however, Congress authorized President Bush to use force in Iraq, and on March 21, 2003, the U.S. began its invasion. On March 27, 2003, of the same year, Tether's statement to the House of Representatives provides the first glimpses of his shift in focus towards to "bridging the gap" between fundamental discoveries and military use (Tether, 2003b), and his May 14, 2003 statement to congress includes a note that only 5% of the DARPA budget is meant to be for fundamental research (Tether, 2003a). Sometime during this period, the slogan "Bridging the Gap" subsequently becomes part of the logo for DARPA. Whether in response to the September 11th attacks and the Iraq war, the need to customize commercially-made products, or due to other reasons, under Tether's rein, DARPA has made many changes, as documented in Table 2.

Table 2: Shift in DARPA Funding Mechanisms 1992-2008.

	Pre-Tether (1992-2000)	Post-Tether (2001-2008)
Δ in DARPA Funding Structure	Funding primarily of university-based research	Funding shifted from universities to industry (especially, established vendors)
	Broad Area Announcements (BAA), Few checks and balances on meeting program targets	Multiple phase solicitations: 12-16 month intervals, Funds tied to go/no-go reviews linked to specific deliverables
	Solicitations open to anyone being the prime contractor	Many soliciations preclude universities and small start-ups as prime contractors, instead requiring the formation of teams with the established vendors as the prime contractors

These changes in DARPA policy brought on an outcry from the computing community (JointStatement, 2005; Lazowska and Patterson, 2005; Markoff, 2005). Although overall funding by DARPA has remained constant, the proportion going to university researchers has dropped by nearly half (Lazowska and Patterson, 2005; Markoff, 2005). Several other policy changes at DARPA in the past seven years have further acted to discourage university participation and signaled a shift from pushing the leading edge of research to "bridging the gap" between fundamental research and deployable technologies (JointStatement, 2005; Lazowska and Patterson, 2005). Today DARPA has increased classification of research programs and increased restrictions on the participation of non-citizens (JointStatement, 2005; Lazowska and Patterson, 2005). In strong contrast to the historically well-known flexibility and discretion of DARPA's broad area announcements, today's funds are tied to "go/no-go" reviews linked to specific deliverables and applied to research at 12- to 18-month intervals (JointStatement, 2005; Lazowska and Patterson, 2005; Markoff, 2005). Further, many solicitations now preclude universities and small start-ups from submission as prime contractors, instead requiring the formation of teams and forcing start-ups and universities to hook up with large established vendors (DefenseScienceBoard, 2005).

4. Industry Background: A Changing Landscape in Computer Science in the United States

The robustness of DARPA over five decades to changing political and economic times is indeed a testament to its design as an organization. This changing political and economic environment, however, has in many ways been the least of DARPA's challenges. As or more challenging has been how the steady evolution and maturing of the computing industry, to which DARPA's support has been so fundamental, has led DARPA to have to learn to work within dramatically different industry and market structures and on technologies of dramatically different maturity. Thus, while the institutional changes led by Tony Tether in 2001 were met with great criticism from the academic computing community, it is important to note that they were preceded by dramatic changes in computing in the structure of the industry and of market demand. Thus, by the time Tether took office, the environment necessary for his change, was already in place.

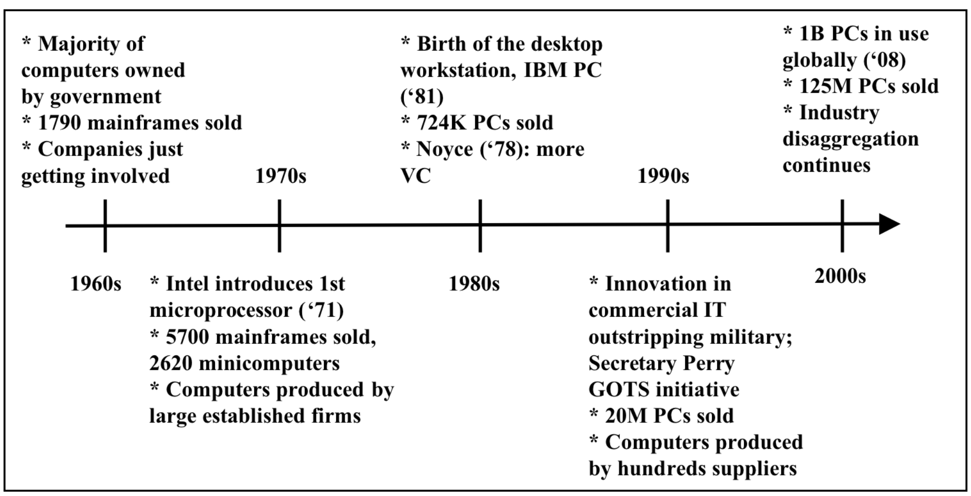
4.1. Computing: Changes in Industry Structure, Market Structure, and the Sources of Innovation

Industry structure and the location and structure of demand have changed dramatically in computing over the past 40 years. In 1960, as DARPA was moving beyond its initial role in space activities, the majority of computers were owned by government. In that year, a total of 1790 mainframes were sold, and companies were just starting to get involved in computing (NRC, 1999; HSUS, 2008). In the 60s, computer science was just starting to emerge as a field (NRC, 1999). By 1970, the number of mainframes sold had more than doubled to 5700, and 2620 minicomputers were also sold (HSUS, 2008). In 1970, computers were produced by large established firms (NRC, 1999). In 1971, however, Intel introduced its first microprocessor, an event which would change the face of computing over the upcoming decades (IntelMuseum, 2008). By 1980, the first desktop workstations were beginning to emerge – with the Apple II introduced in 1977 and the IBM PC in 1981. Alone in 1980, 724,000 personal computers (PCs) were sold (online reference). In accepting the IEEE Medal of Honor in 1978, Robert Noyce – founder of Fairchild Semiconductor and later of Intel, called for greater venture capital – a call that would come to define the structure of R&D and of the industry in the upcoming decade. In 1990, 20 million PCs were sold globally, and computers were produced by hundreds of suppliers (online reference) (Bresnahan and Greenstein, 1999). These shifts are shown in Figure 1.

These changes in industry and market structure have significant consequences for the way innovation can be managed, as well as where power and influence lie over the future of technology directions. In the case of computer servers and systems, the cutting edge of technology has to a large extent moved from niche to high-volume markets. In 1960, high-end mainframe computers were entirely purchased by defense contractors. By the 1980s, the computer market could be divided into three types of demand – business data processing in organizations (met with mainframes), business individual productivity applications (met with

PCs), and technical computing (met with minicomputers.) The rise of networked computing technologies led to a convergence of these markets. In particular, networks of personal computers and workstations were able to compete with (and eventually overcome) many minicomputer and mainframe markets (Bresnahan and Greenstein, 1999). By the 1990s, innovation in commercial IT was outstripping that of the military. As a consequence, in 1991 Defense Secretary William Perry announced the DOD Strategic Acquisition Initiative (SAI) which mandated that defense contractors first look at commercial off-the-shelf (COTS) products when developing new technology upgrades, and in 1994 Perry issues his defining memorandum, "Specifications & Standards – A New Way of Doing Business" – which became known as the COTS Initiative, and mandates the preference for commercial products (Saunders, 2004). In 1997, Defense Secretary William Cohen launched the Defense Acquisition Reform Initiative to Accelerate COTS (Saunders, 2004). Today, defense contractors custom-build the front-end, but buy the back-end from industry suppliers. Rapid advances in performance, high production volumes, and the switch to networked systems have helped microprocessors become standard across many traditionally customized computing applications. In the future, high production volumes may even further influence technology directions. Specifically, whereas electronic components for PCs, in particularly DRAM chips and microprocessors, have traditionally dominated technical advance in semiconductors, in the future this technical advance may instead be directed by even higher volume component markets, such as those for cell phones and other mobile computing devices. The implications of these market shifts for the military's ability to develop technology to meet mission goals remain unclear.

Figure 1: Timeline of the Computer Industry Structure and Demand Sources



These changes in industry and market structure have at the same time led to fundamental changes in the way corporate research is conducted in the computing industry. In the earlier part of the 20th century, much R&D was still housed within corporate laboratories such as Bell Laboratories, GE Research, IBM Research, and Xerox Parc (Mowery, 1999; NAS, 2007). These large U.S. corporate laboratories of the 1950s and 1960s performed much of the fundamental research that underlies today's mainstream semiconductor technology (Macher et al., 2000). In 1980, IBM still conducted 50% of the R&D in the computing industry (NRC, 1999). Beginning in the 1980s, however, a combination of competitive pressure, the perception of disappointing returns from investments in R&D, and the change in federal antitrust policy led many U.S. firms to "externalize" a portion of their R&D operations (Mowery, 1999). Today, complex networks of firms and close collaborations between users and producers of hardware and software now play an important role in developing new products. However useful, collaborative R&D in the U.S. semiconductor industry has supported little long-term research (Macher et al., 2000). Although the leading U.S. merchant semiconductor firms, such as Intel, TI, Micron, and AMD, spend 10-15 percent of revenues on R&D, the bulk of these expenditures focus on new product development (Macher et al., 2000). Further, none of the new leading small firms in digital communications maintain internal semiconductor R&D; instead focusing their efforts on product definition, system design, and marketing of their end products (Macher et al., 2000). Today, the game in the computing industry is part integration (whether an idea or a component), rather than new (from scratch) inventions (Iansiti, 1997). (See Table 3.)

Table 3: Shifting Innovation Ecosystem and Industry and Market Structures in Computing

	First Three Decades (1950-1980)	Recent Three Decades (1980-present)
Δ in Innovation Ecosystem	Corporate R&D Labs (Macher 2000; Mowery 2000; NAS 2006)	Increased reliance on external sources of R&D (Mowery 1999)
	Firm-based innovation trajectories	Complex networks of firms, universities, government labs. Interdependency of innovation trajectories across products (NRC 1999, Mowery 1999:7, Powell and Grodal 2005)
Δ in Industry Structure	Few pioneering firms supplied computers	Hundreds loosely linked suppliers (Bresnahan 2000)
	Primary demand government contractors	Primary demand (high volumes) commercial applications
Δ in Demand	Government contractors order customized products	Government contractors customize commercial products

3.2 Computing: The Changing Quantity and Sources of Government Funding

In parallel with these dramatic shifts within the computing industry itself has been a shift in the nature and structure of government funding of computing research and development. Substantial government, especially military, research funding backed the development of many of the technical and systems capabilities in the early U.S. computer industry (Bresnahan and Greenstein, 1999; NRC, 1999). Roughly 70 percent of total university research funding in computing between 1976 and 1990 came from the federal government (NRC, 1999). More than half the papers cited in computing patenting applications in 1993-1994 acknowledge government funding (NRC, 1999). By 1992, however, the total percent of federal funding for computing research had significantly declined.[2]

[2] Federally funded R&D in the U.S. computing and semiconductor industries (here based on SIC 367, electronic components) declined from nearly 25 percent of total R&D spending in 1980 to slightly less than 7 percent in 1992

At the same time, there has been a significant change in the sources and structure of this government in the last two decades. Since the early 1960s, the federal agencies most responsible for supporting computing research have been the National Science Foundation (NSF), the Defense Advanced Research Projects Agency (DARPA), and the Department of Energy (DOE) (JointStatement, 2005). In 1998, NSF and DARPA bore a leading and nearly equal share of the overall federal investment in IT R&D, with DARPA funding 30 percent and NSF 27 percent (JointStatement, 2005). However, as the overall government funding of computing research has increased, DARPA's share – both as a percentage of the overall effort and in absolute dollars – has declined. By 2005, while NSF represented 35 percent of overall federal IT R&D funding, DARPA represented just 6 percent (JointStatement, 2005). Unlike the NSF, which awards peer reviewed grants and funds a broader set of institutions (NRC, 1999), DARPA is historically known for its "blue sky" funding, large discretion and flexibility, bets on vision and reputation, and ability to create and nourish communities of researchers to focus on problems of particular interest to the agency. As a consequence, DARPA is frequently seen as critical in seeding and encouraging new technology directions and fields in the U.S. (NRC, 1999; Roland, 2002; JointStatement, 2005; Markoff, 2005). With the decline in DARPA's proportion of overall funding and DARPA's recent changes in policy, many see this traditional role of DARPA as threatened. (See Table 4.)

Table 4: Shifting Structure of Government Funding for Computing

	Federal Investment in IT R&D (1998 snapshot)	Federal Investment in IT R&D (2005 Snapshot)
Δ in Fed. Investment in Computing	Federal Investment in IT R&D: DARPA 30% NSF 27%	Federal Investment in IT R&D: DARPA 6% (total investment constant) NSF 35% (total investment has risen) (JointStatement 2005)

5. Methods

This paper uses grounded theory-building methods (Glasner and Strauss, 1967; Eisenhardt, 1989; Yin, 1989) to unpack the processes by which DARPA fosters new technology trajectories within the innovation ecosystem. Using case study research, I focus on four materials technologies funded by DARPA and critical to the advancement of Moore's Law. Two of these technologies – SiGe and strained Si – received DARPA funding in the mid-90s and were subsequently introduced into microprocessor designs and mainstream Si-CMOS production lines. The remaining two materials advances – 3D packaging technology and integrated photonics – are in early stages of DARPA funding and development, but are identified by the ITRS Roadmap and in academic publications as potentially critical to continuing Moore's Law in the upcoming decade. All four of these technologies are technologies invested in by program managers within DARPA's Microsystems Technology Office (MTO), which until April 1999 went by the name of the Electronics Technology Office (ETO) (Reed, 1999).

(Macher, Mowery, and Hodges 2000). This is due, in large part, to a rise in industry computing research funding from 1983 to 1990. Industry research funding for computing dropped to government levels by 1994, but by 1996 were back to their 1992 values (NRC 1999). Government funding for computing continued to rise slightly between 1990 and 1996 (NRC 1999).

To study these cases, I triangulate participant observation, qualitative interview data, archival data, and bibliometric data to provide a holistic view of the forces driving technological change (Jick, 1979). My results primarily draw from 50 semi-structured interviews with scientists and technologists (including DARPA program managers) who were involved in the development of the SiGe, strained silicon, integrated photonics, and optical interconnect technologies between 1992 and 2008. I identify key scientists and technologists in the "invisible college" {Crane, 1972 #457} in this technical area through a snowball effect based on names mentioned in early interviews and in news documents. I subsequently cross-checked this list and identified additional DARPA program mangers involved in funding these technologies using DARPA's online archives for the period. All together, I executed the interviews so as to ensure that they included (1) DARPA program managers from both before and after Tony Tether took the directorship,[3] and (2) a representative cross-section of scientists and technologists from within academic institutions, start-ups, and the five established microprocessor vendors – Intel, AMD, IBM, HP, and Sun. I also asked each respondent to provide an up-to-date biography and CV, including a list of all of their publications and patents to-date in their career. I use these individual CVs to better understand the bibliometric records of each interviewee, as well as they co-patenting and co-publishing records with other scientists.

I conducted several participant observations throughout the course of the study to gain insights into both the optoelectronics and microelectronics industries and DARPA's role in technology development. Early on, I was able to conduct a three-hour participant observation of a DARPA-funded team in the process of developing its technology so as to acquire Phase II funding. I was also able to attend multiple industry conferences throughout the course of the study, due to my own technical activity in the area during my dissertation, through additional connections from my interviews, and through my ongoing professional activities studying the converging telecom and computing industry. These industry conferences included three of the Bi-annual Microphotonics Industry Consortium conferences (Fall 2007, Spring 2007, Fall 2008), Phontics North 2007, the 2007 IEEE Computer Elements Vail Workshop, the Optoelectronics Industry Association (OIDA) 2008 Annual Forum, and the OIDA Manufacturing and Innovation in the 20th Century Workshop in Spring 2008.

Finally, I have been able to draw on extensive archival data available through the CMU libraries, online, and saved within the personal collections of David Hounshell. DARPA provides a wealth of archival data online, as well as through their technical archives. In addition, a host of information about both DARPA and company initiatives can be found in the popular press, congressional hearings, and in industry trade journals. Together, I use these online DARPA archives, the available news sources to document DARPA solicitations, workshops, conferences, and press releases as related to the four materials technologies.

6. Results and Discussion

Over the past twenty years, DARPA, the computing industry, and the U.S. innovation ecosystem have all undergone tremendous change. In the first section of the results, I identify five characteristics of DARPA as an organization that frame its success in seeding and encouraging new technology trajectories throughout the decades. The section also sheds insights

[3] In the course of data collection, significant challenges emerged in gaining clearance to interview current DARPA program managers. After extensive discussions, I have received clearance for interviews with four critical program managers. These interviews are set for July 9-10 at DARPA headquarters in Washington, D.C., and will be included in the final paper by September 2008.

into what about DARPA has enabled it to be so robust to changing political, economic, and technical times. The second section of the results then draws on interviews of DARPA Microsystem Technology Office program managers and technologists in the field they funded from industry and academia to unpacks five distinct steps by which DARPA program managers during the period from 1992 to 2001 seeded and encouraged new technology trajectories. The third section of the results then explores the changes within DARPA since 2001. Here, I again draw on archival data and interviews with academics, industry members, and program managers but instead from 2001-2008. This section again proposes five methods by which DARPA seeds and encourages new technology trajectories, and compares these methods, and the recipients of their efforts, to those found in the previous period.

6.1. DARPA: The Institution

Despite the many changes both within DARPA and in its external environment, a number of characteristics, interpreted differently during different periods of the organization, have been claimed to be as paramount of DARPA as an organization. Richard VanAtta, a long-time observer and writer on DARPA, summarizes the DARPA organizational environment into three key characteristics: (1) it is independent from service R&D organizations, (2) it is a lean, agile organization with risk-taking culture, and (3) it is idea-driven and outcome oriented (VanAtta, 2007). These themes are echoed in DARPA's self-described 12 organizing elements, along with two additional themes – a focus on hiring quality people ("an eclectic, world-class technical staff"), and the importance of DARPA's role in connecting collaborators (Bonvillian, 2006). Again the extent to which these additional two themes have been a focus, and how they have been applied within the organization has varied over the years. This paper does not focus on DARPA's organizational structure, per se, but rather on the specific processes by which DARPA influences technology trajectories. It is thus the last theme of connecting -- also found in VanAtta's articles and in Roland's research on the strategic computing initiative -- on the which this paper places the greatest focus (Roland, 2002; VanAtta, 2007). Inevitably, however, DARPA program managers act within and are influenced by the institutional environment and organizational structure of DARPA. I begin, therefore, by highlighting five aspects of DARPA particularly significant to understanding how its program managers influence the direction of technical change.

6.1.1. A Culture Which Supports Risk-Taking

(At DARPA you can) … place bets with enormous risk, and very few penalties of failing. It's probably better to have spectacular *failures than just lots of failures.*

Among the many books and articles which over time have been written about DARPA it is often suggested that critical to DARPA's success in enabling revolutionary new technologies is it's risk-taking culture (NRC, 1999; Roland, 2002; Bonvillian, 2006; VanAtta, 2007). The interpretation of what constitutes DARPA's mission of "advanced technology development" and what constitutes a risk-taking culture has varied with the DARPA director and the climate of the times (NRC, 1999; VanAtta, 2007). For example, both Heilmeier in the 1970s, and Tony Tether, in his current position, have placed emphasis on short-term milestones, and discontinuing programs unable to meet their deliverables (NRC, 1999; Tether, 2002). This does not necessarily mean that the programs themselves even during those times were not risk-taking.

As explained by one university professor, this risk-taking funding perspective can "play a huge role in selecting key ideas." This university professor, who has received DARPA funding throughout his career, describes the significance of DARPA funding in the scheme of NSF and other funding options.

NSF is much more peer-review, . . . When you have a huge peer review and so on, if something is too radical, it gets killed. So you kind of get the lowest common denominator funded. But with DARPA, they'll take flyers. They'll say this is really radical. A huge chance of success or a huge chance of failure, but a big upside.

6.1.2. Connected, Outcome-Oriented Projects with Long-Term Vision

It is important to note that while individual researchers' projects or even entire DARPA programs may be risky, DARPA is housed within the Department of Defense, and its programs are aimed at advancing technologies toward a specific long-term aim related to military needs. As such, DARPA is far from a pure venture capitalist – both 1) in that it does not fund a project through to market commercialization, stopping instead at the point when the idea has been conceptualized and industry or military missions are ready to take over, and 2) in that while it may not know at the start the exact technologies to meet it's long-term needs, its portfolio of technologies are created with a long-term need in mind. Inevitably, the extent to which individual program managers' research visions have aligned with specific military needs has varied over the years by program manager and by the director at the time. Likewise, the extent to which a given DARPA office and a given DARPA program manager have a single vision varies, but inevitable they must write a succinct research program as part of their application to become a program manager. J.C.R. Licklider, for example, had a clear vision of "man-computer symbiosis" when he came to ARPA to head IPTO in 1962 (NRC, 1999). Licklider's successor, Robert Kahn, first conceived the Strategic Computing Initiative as a pyramid of related technologies (Roland, 2002). In this scheme, progress would materialize as developments flowed up the pyramid from infrastructure at the bottom through microelectronics, architecture, and artificial intelligence to machine intelligence at the top. The goal of the Strategic Computing Initiative was to develop each of these layers and then connect them (Roland, 2002). A similar pyramid approach is being followed in the Microsystems Technology Office by its director, Robert Leheney today. In contrast, Steven Squires, briefly director of the Information Science and Technology Office, and later director of the Computer Systems Technology Office, envisioned research as a continuum. Instead of single technologies to serve a given objective, he sought multiple implementations of related technologies. He called this array of capabilities from which users could connect different possibilities to create the best solution "grey coding" (Roland, 2002). As described by Roland, "His research map was not a quantum leap into the unknown, but a rational process of connecting the dots between here and there" (Roland, 2002). During my own interviews, DARPA program managers from the last decade and a half described some times where they funded multiple researchers working on the same technology, and other times where they funded researchers with different technology options to compete against each other toward achieving a common performance goal.

6.1.3. Little Hierarchy

DARPA was created to have little bureaucracy or hierarchy. To get a new project funded, a program manager need only go through two approval steps – his or her office director, and the director of DARPA. One DARPA program manager describes his experience in this environment as follows,

I mean you could just turn on a dime. We could basically call people up, and have a discussion. With the idea that if we see something here, we could fund a seeding, and get something and see if there's a next step.

To further prevent bureaucracy, DARPA is organized such that turnover of personnel is generally high. Neither DARPA program managers, nor the office directors, nor the director him or herself are life-long bureaucrats. Instead, they are pulled from the research community within academia, industry, or the government labs for brief periods of their careers. The period each of the DARPA directors held office is shown in Appendix 2. As can be seen, the mean directorship has been 2.7 years, and the mode, 2 years. Similarly, while there are some exceptions, and several cases where program managers later come back for a second period as an office director, both office directors and program managers generally hold their positions for no more than 3-5 years. While office directors and even program managers often choose their successor – thus helping create continuity across research programs, this turnover helps continually bring in new ideas and new social networks into the DARPA office. This turnover, especially of the director, also helps DARPA remain flexible and resilient to changing political and environmental times.

6.1.4. The Program Manager

It really comes down to the program manager. A program manager that has a passion for an idea, that understands the technical elements of an idea, and has some vision for where it might go.

- DARPA Program Manager

To understand the role of DARPA in influencing technology development, one must start with the public servants who are on the ground. Program managers are traditionally taken from the existing research network – including government labs, universities, or industry. Although program managers can be professors, they do not even need to have Ph.D.s. The role a program manager is known historically within the technical community not only as a stepping stone to higher positions, but also as one of the more exciting opportunities within one's career, involving much freedom and influence over the future of technology.

6.1.5. The Role of Relationships

Since its beginnings, DARPA has been known for working off of relationships. In the 60s, most of its funding went to a few elite institutions – MIT, Carnegie Mellon, Stanford, and a few other schools – with the austensible goal of supporting the best people and their graduate students in a context promising positive reinforcement among the different programs (Roland, 2002). According to Roland, the IPTO most often filled its vacancies by unilateral invitation to members of what came to be known as the "ARPA community." This community consisted of those researchers who regularly get ARPA contracts, and sit on ARPA advisory boards (Roland, 2002).

Today, DARPA continues to be known within the technical community as making funding decisions based on relationships. Program managers pull on their existing social network from prior to taking the position – a network which frequently grows after rising to the role of program manager. Regardless of whether a conversation is with a DARPA program manager, a university professor, or a member of industry; as shown in Table 5, talk about DARPA funding decisions emphasizes the importance of relationships.

Table 5: The Role of Relationships in DARPA Funding Decisions

DARPA Program Manager	University Professor
… I knew there was a chance they wouldn't make it. But at the time, I was betting on the person. Usually, I'd bet on a few people.	*And then he (DARPA program manager) touched on people like (professor's name) and others who he knew well, and said, hey, help me, give me the ideas. So, he touches on (same professor's name), he touched on other key leaders in the field that he knew and trusted*

This networked approach, inevitably has its pros and cons. Researcher of social networks have long commented on the existence "communities of practice" and "invisible colleges" in which knowledge flows (or "leaks") easily across firm and institutional barriers between researchers of common discipline (Crane, 1972; Allen, 1983; VonHippel, 1987; Brown and Duguid, 2001). DARPA program managers are inevitable brought into their positions out of this community. Once in their positions, as "100 geniuses connected by a travel agent" (Bonvillian, 2006) they further their ties and understanding of the disparate activities within this community. It is specifically through these strong ties with researchers in the community and intimate knowledge of their research activities, that DARPA program managers are able to do the type of connecting of ideas introduced in section 5.1.3, and unpacked in great detail throughout this paper. At the same time, tightly knit social networks have been shown to lend themselves towards "group think" (Powell and Grodal, 2005). The extent to which DARPA program managers are able to avoid "group think" through their travels to visit researchers and extend their network, will inevitably vary greatly by program manager. Further, the extent to which the turnover of personnel within DARPA may help prevent such "group think" in DARPA as a whole, may depend on the selection processes for the director and office managers. Even here, trade-offs remain between selecting new directors so as to support continuity of programs versus the bringing in of new ideas. Alone, the extent to which DARPA has morphed over the years to meet the changing political and technical environment, suggests that at an organizational level, the DARPA has proved quite adaptive and resilient, and perhaps avoided a certain amount of long-term "group think".

6.2. DARPA in the 1990s (1992-2001)

The section which follows draws on archives and interviews from academics, industry members, and DARPA program managers active during the period from 1992-2001. Based on these interviews, DARPA archives, and press releases, I identify five processes by which DARPA program managers during this period tap into existing social networks to seed and encourage new technology trajectories. These five processes are (1) identifying directions, (2) gaining momentum, (3) building community, (4) validating new directions and (5) not sustaining the technology. I describe each of these processes in detail, and their significance below.

(1) Brainstorming Ideas, Identifying Directions

In understanding the role of DARPA program manager, one important questions is the extent to which DARPA program managers come with a vision, or act as a place to which researchers within the field with a vision can come. The answer is inevitably both. Industry and academic researchers consistently describe themselves as the people with the ideas, and DARPA program managers as the people who funded them, provided legitimacy, and helped provide the funding and community support to bring the vision to fruition. Yet, in this very role, whether as funder or knowledge-holder, the DARPA program manager becomes a central node to which information from the research community flows. Further, in understanding long-term military goals, it is the DARPA program manager who is in closest contact and, in some cases, the single bridge between the research community and the world of defense. Thus, as described by the DARPA program managers themselves, they are not the "windows" for ideas, described by Block (Block 2007), rather they are the symphony directors written about by Roland. Still, this analogy is lacking, since the researchers do not merely play pre-defined notes on pre-defined instrument, but instead bring ideas to the DARPA program managers, which in turn shape their symphony. This two-dimensional role takes two forms within DARPA -- bringing leaders together for brainstorming to identify technology directions to meet agency mission goals (discussed yet in this section under point (1)), and seeding disparate researchers to gain momentum around common themes (discussed in the next section under point (2)). In both cases, the DARPA program managers are in constant contact with the research community, understanding emerging research themes, and choosing the right players to bring together.

DARPA has both formal and informal methods for bringing together top scientists to brainstorm research directions to meet mission goals. Among its formal mehods, the DARPA-Defense Science Research Council holds an annual summer conference which brings together "a group of the country's leading scientists and engineers for an extended period, to permit them to apply their combined talents in studying and reviewing future research areas in defense sciences" (DSRC, 1997). At this summer conference, top scientific and technical researchers in the country are exposed to major problems facing the U.S. military, and asked to leverage their expertise to identify technological directions to solve these challenges. During the year, workshops and program reviews are attended by smaller groups of the Council members, whose reports are made directly to DARPA (DSRC, 1997). In addition to the annual summer conference and these workshops, other relevant formal advisory activities include broader Department of Defense efforts to identify technology directions including Defense Science Board (DSO) task forces, and Information Sciences and Technology Study Groups (ISAT).[4] Task forces by the DSO[5] or ISAT can be called to address specific topics or challenges of interest to DARPA. For example, a

[4] ISAT has similar workings to the Defense Science Board task forces, but are focused on military challenges associated with information technology.

[5] The DSO was established in 1956, in response to recommendations of the Hoover Commission. Today, the DSO's authorized size is 32 members selected for the preeminence in science and technology and its application to military operations, and seven ex-officio members. The task force consists of DSO board members, and other selected consultants or experts. DSO`, 2008. "Defense Science Board: History." Retrieved November 3, 2008, 2008, from http://www.acq.osd.mil/dsb/history.htm.

February 2005 DSO task force focused on High Performance Microchip Supply, a primary area in which work is being conducted by DARPA, and included representatives from industry and the government, including DARPA. Finally, DARPA also has a long history of gaining outside council from elite, and technology-oriented organizations, through funded studies by the Jasons, and independent labs such as Lincoln Labs and MITRE.

DARPA is not limited to holding these brainstorming sessions to identify directions within these formal committees. Brainstorming sessions can also be called together by individual DARPA program managers, and can be much more informal. One DARPA program manger describes his role in bringing scientific leaders together around a common theme,

We were talking with Paul Robinson about the notion of building very very high volume carbon nanotubes that were functionally matched…. And I said, gee, Rick's always been working in that area, let's just call him in. Rick's a noble prize chemist. So we called him. He was there in two days. And so Lieber came over from Harvard. We sat around. And it was a great discussion.

The above-described interaction occurred in the mid-90s. Here, in supporting innovation DARPA program managers are the cocktail hosts described by Lester and Piore in *Innovation: The Missing Dimension* (Lester and Piore, 2004). Thus, the DARPA program managers select the members of the party, and help start the conversation necessary to brainstorm and identify the necessary new directions. Notably, as shown in Table 6, all of the people at the above-mentioned gathering, with the exception of the DARPA program manager, could be characterized as Zucker's "star scientists" (Zucker and Darby, 1996). None of them, however, have bibliometric or other paper trails of intellectual ties with each other. These results are in striking contrast with the majority of social networks research, which focuses on documenting collaborations through patent co-authorships. They are thus suggestive that it is precisely these critical, early-stage, informal, direction identifying, technical conversations which can not be found in biliometric studies.

Table 6: Mid-90s Collaborators Brought Together by a DARPA Program Manager to Brainstorm on Carbon Nanotubes

	Paul Robinson	Richard Smalley	Charles Lieber
Occupation, mid-90s	President, Sandia Corporation and Laboratories, Director Sandia National Labs	Professor Chemistry, Physics, Astronomy, Rice University	Professor, Chemistry, Harvard University
Total Patents	?	>90	>30
Total Publications	?	>394	>290
Lifetime Achievements	Elected member NAE, Outstanding Public Service Medal from Joint Chiefs of Staff	1996 Nobel Prize for discovery of "buckeyballs"	Elected member NAS
Co-authorships with each other	None	None	None

(2) Gaining Momentum: Seeding Disparate Researchers

The previous section describes a DARPA program manager facilitating in-person brainstorming between scientific and technological leaders in the field around a particular technological goal. In gaining momentum around a technology direction, however, the DARPA program manager need not necessarily, or at least immediately, bring everyone into the same geographic space. One DARPA program manager explains,

So I'll tell you the SiGe story…. So, the first guy to show me this, actually two guys, … was the guy who founded Amberwave. He showed me this is possible. And then Jason Moo and UCLA, … he showed me a plot of bandgap as a function of percent Ge. And he had two plots. He came to DARPA. And he said, look, there is a dependency, here it is, it follows band gap theory. … And I said, 'Jason, two dots don't make a program…. I need a third dot.' And he faxed me a chart the next day. … So I sent him a small seeding.

At the same time I called Bernie (a fellow at IBM), and I said, 'Bernie, have you ever seen this bandgap dependency in SiGe? You know, do you think it's something we can exploit?' He said, 'Funny you should ask. We've been looking at the same thing, and we've got some ideas as well.' So I funded him $2M or whatever it was.

As can be seen in combining the above quote and Table 7, the DARPA program manager is in contact with three star researchers, working in the same area. In this function, he is neither acting as a broker—connecting otherwise disparate actors; nor as a boundary-spanner – identifying, translating, and relaying information across firm, cultural, or technical boundaries; in the traditional sense (Fleming and Waguespack, 2007). (According to these definitions, brokers can span boundaries, but not all boundary-spanners can broker.) Instead, the DARPA program manager is simply seed-funding these disparate researcher, perhaps relaying some knowledge about the one to the other or about general activities in the technical community, and not necessarily at first bringing them together at all. These results are significant given the results by Zucker and Darby, which suggest that star scientists are very protective of their techniques, ideas, and discoveries in their early years, tending to collaborate most with their own institution, which slows diffusion to other scientists (Zucker and Darby, 1996).

Table 7: Technologists Funded by a DARPA Program Manager to Gain Momentum around Si Ge and Strained Si Technology

	Eugene Fitzgerald	Bernard Meyerson	Jason Woo
Occupation, mid-90s	Associate Professor, Materials Science and Engineering	IBM Fellow, Group Director	Professor, Electrical Engineering, UCLA
Occupation, 2008	Professor, Materials Science and Engineering	IBM Fellow, V.P. and Chief Technologist, Systems and Technology Group	Professor, Electrical Engineering, UCLA
Total Patents	>15	>40	?
Total Publications	>186	>180	>100
First paper in SiGe	1986	1986	1991

technology			
Evidence of co-authorships with each other, or other cooperation	None	None	IBM Faculty Award, 1998

(3) Building Community: Increasing Information Flows, Growing the Base

The above results also have a second significance. In receiving funding from DARPA, researchers are required to present to each other in workshops, thus further pushing the flow of knowledge around early-stage ideas. Similar to the results in section (1), background research on the technologists referenced by the DARPA program managers show both Eugene Fitzgerald ("the guy who founded of Amberwave") and Bernard Meyerson ("Bernie") again to be what Zucker and Dary would classify as star scientists (Zucker and Darby, 1996). Fitting with their classification as star scientists, neither Gene or Bernie – who are at different institutions – have never co-patented or co-published. Yet, through DARPA, Bernie and Gene were brought together in workshops to present to each other their research. Thus, what would otherwise have been knowledge kept within their organization was forced at some level (with the exception of some company-proprietary details which are presented solely to the program managers) to flow between the two. Thus, in funding disparate researchers, DARPA program managers appear to be promoting the sharing of knowledge between star scientists, who left to their own devices would, according to the literature, tend to be very protective of their knowledge. In the some cases, these workshops may even lead to new collaborations. Jason Woo, for example, started in the field a bit later than Bernie or Gene (1991), and, as the 1998 IBM Faculty Award he received suggests, may have even developed a relationship with IBM through his funding from DARPA.

(4) Providing Third-Party Validation of New Technology Directions

In addition to it's role in bringing researchers together to brainstorm new technology directions, seeding disparate researchers to gain momentum around those directions, and bringing those researchers together to share their results, DARPA also plays a fourth role in technology development. Specifically, the actions of DARPA's program managers also provide external validation for new directions. The quotes below in Table 8 suggest that this validation of new technology directions holds weight in industry as well as with other funding agencies.

Table 8: The Role of DARPA Funding in Providing Third Party Validation

DARPA Program Manager	University Professor
So the DARPA piece, while large, was the validation for IBM to spend their own money. The same way for the Intel piece. You know, Intel certainly looked at that project, and then Intel ended up funding it internally, but the fact that DARPA went back to them three and four times and said, this is an important thing, this is an important thing, you know, it got to the board of directors, and it got high enough that they set up a division to do this.	*See, once you've gotten funding from DARPA, you have an issue resolved, and so on, then you go right ahead and submit an NSF proposal. By which time your ideas are known out there, people know you, you've published a paper or two. And then guys at NSF say, yeah, yeah, this is a good thing. … So NSF funding usually comes in a second wave. DARPA provides initial funding. … So DARPA plays a huge role in selecting key ideas.*

(5) Avoiding Reliance on the State
Despite DARPA's role in validating new technology directions both to other funding agencies and in industry, DARPA program managers take note to point out that DARPA is not the sustaining piece in commercializing any new technology. As one DARPA program manager explains,

So we ran all of these design-of-experiment concepts, and you know, … we were doing great stuff, really good science. But the tipping point, … is the fact that IBM saw the value in this to the point that they started investing in it.

This emphasis on not being the sustaining piece for a given technology is an important point. Early studies warned of the tendencies for companies to become reliant of support from the state (Allen et al., 1978; Sirbu, 1978; Zysman, 1983). In the history of DARPA's role in developing technology for the laser, the internet, the microprocessor, and the personal computer, DARPA avoided these pitfalls. More recent studies of small-firm reliance on government funding, however, have shown different results. In particular, a recent National Academies study of SBIR funding, showed that small businesses supported by SBIRs are not particularly successful at commercializing their technologies, however, are very successful at developing technologies which meet the particularly SBIR funding agency's (i.e. DOD, DOE, or NIH) mission goals (Wessner, 2007).

Thus, although there were inevitably failures, historical studies suggest that DARPA's methods of brining together researchers to brainstorm new technology directions, seeding disparate researchers working in the same area to gain momentum around new technology directions, encouraging early-stage knowledge sharing between researchers in workshops, and providing early-stage validation to other funding agencies and industry met great success. Evidence of these successes can be found in numerous historical books, and include early development of laser technology (Bromberg, 1991; Hecht, 2005), photonics (Sternberg, 1992), microprocessors (Malone, 1995) – including the materials technologies (SiGE and Strained Si) focused on in this study and now successfully implemented in large-scale industry production, the personal computer (Allan, 2001) and high-performance computing technologies (NRC, 1999; Roland, 2002), and the internet (Abbate, 2000; Newman, 2002).

6.3. DARPA Under Tony Tether (2001 – present)

As discussed in section 3, the changes in DARPA, initiated under the leadership of Tony Tether, led to an outcry in the computing community. Representative of these changes is the recent DARPA Ultraperformance Nanophotonic Inttrachip Communications (UNIC) program, outlined in Table 9 below.

Table 9: DARPA Microsystems Technology Office (MTO) Ultraperformance Nanophotonic Intrachip Communications (UNIC) Program

	Phase I	Phase II	Phase II
Award Date	February 2006	November 2006	March 2008
Description	Super-seedling, validity demonstration		$44M
Timeline	9 months	2 years	5 ½ years

Primary Contractor Awardees	1. HP 2. IBM 3. Sun Microsystems 4. BAE Systems 5. Analog Devices?	1. HP 2. IBM 3. Sun Microsystems 4. MIT I	1. Sun Microsystems
Additional Team Members	1. ? 2. Luxtera 3. Luxtera 4. MIT I 5. MIT II	1. Intel 2. Luxtera 3. Luxtera 4. MIT I	1. Luxtera, Kotura, Stanford UCLA

In some ways, this UNIC program and the other programs like it at DARPA, are nothing new. They all follow a long tradition of DARPA initiatives supporting technology developments that in the long term contributed to Moore's Law (see Appendix 3). In the case of UNIC, the focus of the solicitation is on photonic integration -- combinations of lasers, modulators, and other devices fabricated on a single chip. As is representative of the broader trends in the computing industry, efforts in photonics integration began in Bell Labs and other research labs in the 60s and 70s. Innovations in photonic integration were in the late 90s pushed forward by small, telecommunications start-ups, due to the technology's potential to reduce product size, improve reliability, and reduce packaging costs. In the long term, the established computing vendors are also interested in these integration technologies due to their potential to bring the higher information carrying capacity of photons into smaller applications such as cell phones, sensors, and computer applications. In addition, developing integration technologies for computer optical interconnects may be critical to sustaining Moore's Law. Roadmaps from Intel and the ITRS suggest that this technology may be needed in the microprocessor industry as soon as 2012. Particularly critical may be the ability of optics to meet challenges communicating core-to-core, core-to-memory, and core-to-accelerator in the new paradigm of multi-core chips.

As can be seen in Appendix 3, DARPA has since as early as 1995 played a significant role in supporting the development of integrated photonics and optical interconnect technologies. As the upcoming section describes, since 2001 the processes by which DARPA program managers tap into their social networks – gaining momentum around ideas, seeding disparate researchers, encouraging early knowledge flows in workshops, and providing third party validation of new technology directions – have remained largely the same. The institutional location of the people into whom they're tapping and the requirements framework within which the solicitations now occur, however, have changed significantly.

(1) Brainstorming Ideas, Identifying Directions

Today DARPA continues to leverage both formal and informal processes to brainstorm and identify critical technology directions, as discussed in 6.2. While the formal and informal processes have stayed the same, the people brought together in these networks may, indeed be different. Additional data access would be necessary to study the changing composition of the Defense Science Research Council Summer meetings, and other formal and formal get-togethers.

(2) Gaining Momentum: Orchestrating the Involvement of Established Vendors with Academics

and Start-up Companies

A start-up company founder describes his interactions with DARPA's program managers, and the role the program managers played in gaining momentum in the academic and industrial communities around their ideas.

So DARPA has program managers, and we were talking to them, and they got excited about this project, and they said, let's try to get a program out. So we worked with ... the DARPA program manager, and they got interested in the field, and they got a program out of this. They got a bunch of other people involved in the program.

As noted earlier, however, in this solicitation the start-up company was not able to be a primary contractor on the proposal. Instead, they were forced to team up with an established vendor to receive funding for the project.

(3a) Building Community: Enabling Knowledge Flows and Reducing Technical Uncertainty in a Fragmented Industry

In addition to DARPA program manager roles in gaining momentum around new ideas by linking academic and start-ups with established vendors, in today's model, DARPA funding recipients are required to attend workshops at the end of each multi-month phase, where they present their results to each other. One industry respondent expresses the importance of such an opportunity to coordinate in today's industry environment,

You just can't make anything happen in industry (today) on your own, because it's completely impossible. You have to find a partner, you have to convince your competition this is the right thing to do.

The mandate to present the results of each phase has powerful implications, depending on the people in the room. In the case of established vendors, DARPA workshops may provide them with a critical opportunity to share new ideas and agree (implicitly or explicitly) on technology directions. In response to an early proposal presentation I gave on this work at an industry conference, one university professor angrily responded,

I can tell you what you'll find. I was there (at the DARPA workshop), and they're (the companies) all presenting to each other what they're going to do. They're all talking to each other. And they're all doing the same thing.

(3b) Building Community: Enabling Technology Platform Leadership at the System Level

To enable the necessary technology coordination within the vertically fragmented industry, the new DARPA may be playing a third, critical role. In particular, it is unclear whether in the new, innovation ecosystem, individual entities – whether venture-funded start-ups or the larger established vendors who through new open-sourcing paradigms expect to buy-up their innovations – have the incentive structures necessary to develop the technologies they need. In the course of my interviews, several industry respondents suggested that DARPA played a critical role in establishing system-level coordination, examples of which are provided in Table

10 below.

Table 10: The importance of government funding from the perspective of system vendors.

Established Vendor A	Established Vendor B
You need someone with a longer term horizon. Ten years from now, we want a teraflop of computing. But we don't have more than a six month time horizon.	*Here, the technology is being driven by the systems companies. Very few companies have the resources to do system-level exploration without DARPA funding. DARPA funding is enabling the system players to determine the direction of this technology. If you don't get the system guys involved, you end up getting widgets that don't work in the bigger picture.*

As can be seen in Table 10, the respondents from both established vendor A and established vendor B emphasize the importance of DARPA. In the case of established vendor A, the senior technical staff member focuses on DARPA's significance in providing a longer term horizon. In the quote from established vendor B, the senior technology fellow focuses on DARPA's importance in coordinating technology development across companies, and in particular, for forcing companies who provide technological components in the industry platform to fit with the needs of the broader system.

This third step of the process may be equally important to start-ups. Similar to established vendor B, the founder of one start-up emphasized the importance of developing technology with the broader industry platform and established vendor needs in mind. He explains,

(In contrast to a large company or M.I.T.), "…as a small company, you have to develop a contact. Headhunters…[can] also bring information to you. We are starting to discuss with (large systems vendor)…. They're trying to keep us developing pieces of technology they need.

Within the old DARPA, the mandate to present research – which would have occurred less frequently – may have forced star scientists to divulge information that they might otherwise have kept confidential within their institution. In contrast, in the case of the new DARPA, and the teams it forms between universities, start-ups, and established vendors, this divulgence of information may be critical in supporting the coordination necessary across companies, including competitors, to enable technological change.

(4) Providing Third Party Validation for New Technology Directions

This role of DARPA in enabling knowledge sharing among competitors and thereby in reducing uncertainty around technology directions, need not benefit the established vendors alone. Similar to the third-party validation role described about DARPA in the previous section, a current start-up founder describes a similar role for them from DARPA today. In the case of the start-up company, DARPA's funding acts as a signal validating the start-ups's technology to the broader industrial community. The start-up founder explains,

Investors are highly motivated to see the company succeed. As a consequence, they will lie through their teeth about what the company can do. DARPA funding and ATP funding have the added benefit of communicating to a third party a validation of the technology.

(5) Breeding Reliance on the State?

Not all of the respondents at established vendors or founders of start-up companies were as positive about DARPA as those respondents shown in Table 10. Two examples are provided in Table 11, of respondents less positive about DARPA expressed concerns about government funding being "too far out" or too far from more pressing commercial realities.
Since the time of the interview, however, the start-up has joined an established vendor's team, and acquired DARPA funding for developing the longer-term technology.

Table 11: Industry Concerns about DARPA Funding Drawing them Away from the Necessities of Meeting Commercial Goals

Established Vendor C	Start-up Company
So, <my company> as a whole has just shied away from government funding. ...<Our company> labs, or whatever, they'll get a little DARPA funding, but most of that is, has never, produced anything of value, from a… commercial perspective. That wasn't saying it wasn't of value within the industry, but just trying to delineate.	*Sometimes I'm very nervous about getting too much focus on defense money. I don't want to lose track of the fact that I'm developing products, not technology. DARPA is funding the industry so far ahead. If you're developing for 10 years from now, DARPA is great. But how do you manage not to lose revenue unless the market is starting in now… Some of the technology developed for the next generation – I don't know if it is applicable that well to (now). I'm not sure DARPA's direction is the direction to go. I think… <my company> is ideally placed for (today's technology). But, admittedly, not necessarily for the long term.*

The concerns expressed by established vendor C and by the start-up founder are not necessarily unwarranted. Early research warned of the dangers of becoming reliant on the state for funding (Allen et al., 1978; Sirbu, 1978; Zysman, 1983). While interviews with the pre-2001 DARPA program managers emphasize the importance of the company taking over and not being the sustaining piece of a technology's development, these themes did not arise in interviews with the newer DARPA program managers. A recent study on SBIRs by the National Academy of Sciences also suggests that this focus may have shifted (Wessner, 2007). In particular, the study shows that while small businesses receiving government funding are good at achieving mission goals, they are frequently not successful at surviving in the long-term or at technology commercialization (Wessner, 2007).

7. Conclusions

With the decline of corporate R&D labs and the vertical fragmentation of industries, firms today face new challenges in establishing appropriate sources of new inventions and in coordinating subsequent technology development across the myriad of affected firms. Recent research has documented challenges in the coordination across firms in advancing technology platforms (Gawer and Cusumano, 2002; Iansiti and Levien, 2004), in aligning incentive structures across interdependent firms (Casadesus-Masanell and Yoffie, 2005), and in supporting long-term research within such ecosystems. Little research, however, has explored the role for government, if any, in aiding the coordination necessary across these firms, as well as between established firms, start-ups, and academic actors so as to sustain long-term technology development.

The computing industry provides a classic example of an industry supported with government funding and characteristic of the above-described changes in the innovation and industrial ecosystems over the past sixty years. Three changes have been particularly striking in the computing industry. First, the computing industry has been particularly representative of the decline of corporate R&D labs, and the shift to a vertically fragmented industry structure. Second, at the same time as this shift in innovation locus and industry structure, the computing industry has also matured and experiences a shift in market demand. Specifically, whereas in the early years, primary demand for computing capabilities was from government contractors, today the primary demand for computing products is from high-volume commercial applications. As a consequence, whereas in the past the military ordered customized products from commercial vendors, today the military must add custom additions to commercial products. Along with these changes in the structure of the industry, the industry locus of innovation and the industry locus of demand, has been a dramatic change in the sources and structure of government funding of the computing industry, particularly within DARPA. Together, these dramatic changes in the computing innovation ecosystem and, later, in the structure of one of the most successful funders of innovation within that ecosystem beg for further empirical study to understand the processes, (1) by which an organization can go through such a change, and (2) by which the State may influence technology development in this new environment.

To this end, this study unpacks the institutional environment and corresponding processes by which DARPA program managers seed and encourages new technology trajectories within the U.S. innovation ecosystem. The study focuses on the recent shift within DARPA under the directorship of Tony Tether. In addressing this challenge, this study breaks its analysis of DARPA into two sections – one evaluating the processes used by DARPA under the previous three directors (1992-2000), and the second evaluating the processes used by DARPA beginning with Tether (2001-2008). What is perhaps most remarkable about the results is that despite significant changes over the past seven years in the degree of autonomy of program managers, the way that project funding is structured, and the even the stated goal at DARPA the underlying processes by which DARPA program managers act to seed and encourage new technology trajectories has remained broadly the same.

What has changed, however, is the situations to which program managers apply these processes. Specifically, prior to 2001, DARPA's processes for seeding and encouraging new technology trajectories involved (1) bringing star scientists largely from academia together to brainstorm new ideas, (2) gain momentum around these ideas by seeding disparate researchers, (3) encourage early knowledge-sharing between star researchers through workshops, and (4) providing third-party validation for new technology directions to external funding agencies and industry. These process provided a critical function in supporting the sources of, knowledge flows around, and development of social networks necessary for gaining momentum around new technology developments. In contrast, since 2001, the DARPA program manager's processes for gaining momentum around new ideas involve (1) orchestrating the involvement of established vendors with academics and start-ups, (2) supporting knowledge-sharing between industry competitors through invite-only workshops, (3) providing third-party validation of new technology directions, and (4) supporting technology platform leadership at the system level. These new process may be providing a critical function in supporting the coordination of technology development within industry across a vertically fragmented firm ecosystem while keeping in mind longer-term commercial and military goals.

Missing, however, from this story is what has moved in to fill the function originally played by DARPA prior to it's self-proclaimed focus on "Bridging the Gap" since 2003. One DARPA program manager from the 1990s, when asked about the role of DARPA in funding technologies to support Moore's Law, stated of his time at DARPA,

> *We never state it publicly, but ... I want to fund those companies that will put Intel out of business. I'm not interested in driving Moore's Law. The ITRS roadmap exists, and everyone knows what it is. DARPA is not in the business of maintaining that roadmap. We're in the business of cutting a path across it.*

With the government needing to customize components produced in industry, and putting control of projects in the hands of system contractors, this program manager's perspective seems far from being true still today.

Finally, in seeking to inform science policy, the leaders of DARPA, and the leaders of other State organizations based on DARPA, the most important indicator of the success of DARPA and its program managers may be the structure, diversity, and content of their social networks. Specifically, who is in their advisory committees helping identify directions, who is in the program manager's network out of which they are seeding and gaining momentum around new ideas, with whom are they building community, with which communities do they at a given time hold the clout to validate directions and whom do they have to involve to hold that clout, and to whom are they transitioning the technology.

Appendix 1: The Changing Faces of DARPA

The Advanced Research Projects Agency (ARPA) was founded under President Eisenhower in February1958 by Public Law 85-325 and Department of Defense Directive 5105.41, as a direct consequence to the Soviet launching of Sputnik in 1957 (NRC, 1999). Initially, ARPA was charged with preventing technological surprises such as Sputnik. Many blamed the advent of Sputnik on the rivalry at the time between the military services, and ARPA was set up to cut through that rivalry. After its founding, ARPA's first priority was to oversee space activities until NASA was up and running and to screen new technological possibilities, shutting down those without merit (Roland, 2002). By 1960, all of ARPAs civilian programs were transferred to the National Aeronautics and Space Administration (NASA) and all of its military space programs were transferred to the individual Services. At this point, ARPA was forced to face the question of its longer-term role. President Eisenhower had always insisted that the Cold War was fundamentally a contest between two economic systems, and that it would be won or lost economically, not militarily (Roland, 2002). This perspective, in which the distinction between military and civilian technology was blurred, would stay with ARPA throughout the 1960s.

With space activity oversight behind it, ARPA focused its energies on ballistic missile defense, nuclear test detection, propellants, and materials (NRC, 1999). It was at this time that ARPA took on the role of bringing along ideas that other segments of the nation would not or could not develop, and carrying them to proof-of-concept (Roland, 2002). ARPA's goal was then to transition the technology out of the laboratory into the hands of users or producers who should bring it to full adoption and exploitation (Roland, 2002). ARPA's independent status not only insulated it from established service interests, but also tended to foster radical ideas and keep the agency tuned to basic research questions (NRC, 1999). When the agency-supported work became too much like systems development, it ran the risk of treading on the territory of a specific service (NRC, 1999). ARPA also established in the 1960s its critical organizational infrastructure and management style: a small high-quality managerial staff, supported by scientists and engineers on rotation from industry and academia, successfully employing existing DOD laboratories and contracting procedures (rather that creating its own research facilities), to build solid programs in new, complex fields (Barber Associates, 1975; NRC, 1999). Finally, according to NAS, ARPA emerged as an agency extremely sensitive to the personality and vision of its director (NRC, 1999).

Following Army Brigadeier General Autin Betts[6], Jack Ruina took the office as DARPA's director in 1961 at the same time as Kennedy and MacNamara took office. As director, Ruina cemented the agency's reputation as an elite, scientifically respected institution devoted to basic, long-term research projects. Ruina believed independence and intellectual quality were critical to attracting the best people, both to ARPA as an organization and to ARPA-sponsored projects (Barber Associates, 1975; NRC, 1999). A Doctor of Electrical Engineering and professor at the time of his leave at the University of Illinois, he also valued scientific and technical merit above immediate relevance to the military (MIT website) (NRC, 1999). During his tenure, Ruina decentralized management at ARPA, and began the tradition of relying heavily on independent office directors and program managers to run research programs. To meet his goals for the

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[6] Betts, the second ARPA director, had suffered under the perception within the Pentagon that he favored his own service. On his recommendation, all subsequent ARPA/DARPA directors have been civilians. (Roland, 2002 #418)

agency, Ruina encouraged creative use of existing Department of Defense managerial mechanisms including "no-year money," unsolicited proposals, sole-source procurement, and multi-year forward funding. (NRC, 1999)

During the 1970s, the war in Vietnam became the driving force, tending to redirect research towards military purposes and raising concerns about the effect of defense funding on university research. In 1969 Richard Nixon became the 37th president of the United States. The Nixon administration pushed for more directed research programs in computer science that addressed specific national problems, rather than letting the research community have most of the role in defining research directions (NRC, 1999). In 1969 Congress forbade military funding for any research that did not have a "direct or apparent relationship to a specific military function or operations" (NRC, 1999). The legislation, which was enacted into law as the Mansfield Amendment to the Defense Authorization Act of 1970 (Public Law 19-121), was short-lived, but had the longer-term impact of shortening the time horizons for government research support in general and defense research in particular (NRC, 1999).

Following the changes in the political climate, ARPA's name was officially changed to DARPA (the Defense Advanced Research Projects Agency) in 1972. In 1975 George Heilmeier became director of DARPA, and brought an emphasis on applications and a more formalized management style (NRC, 1999). Under Heilmeier's directorship, all proposals needed to address six questions: (1) what are the limitations of current practice, (2) what is the current state of technology, (3) what is new about these ideas, (4) what would be the measure of success, (5) what are the milestones and the "mid-term exams, and (5) how will I know you are making progress. In contrast to Ruina, Heilmeier led with a heavy-hand, giving all DARPA orders a "wire brushing" to ensure that they had concrete "deliverables" and "milestones" (Roland, 2002). In short, Heilmeier viewed DARPA as a mission agency, whose goal was to fund research that directly supported the mission of the DOD (Roland, 2002). Attempts to transition some of the IPTO paper studies to applications brought an infusion of 6.2, or Exploratory Development, funding to the IPTO in the early 1970s. Heilmeier accelerated that trend, flipping the distribution of basic-to-applied research funding from 60-40 to 42-58 during his tenure, while holding the total IPTO budget stagnant. While Robert Kahn had no difficulty justifying his networking projects to Heilmeier, artificial intelligence fared less well, and Heilmeier, by his own account, sent the AI community – which was at the time focused on more basic research – into turmoil (NRC, 1999).

In the 1980s, fears were raised that the microelectronics and computer industries seemed to be going the way of the auto industry – to Japan, and defense concerns gave way to industrial competitiveness as the primary driver of research policy. These fears were not unfounded. During the 1980s, the U.S. semiconductor industry's share of the global market fell from 75 to 40 percent (Alic et al., 1992). By the end of the 80's Japanese semiconductor manufacturing equipment suppliers were gaining market share at a rate of 3.1 percentage points a year, and u.S. semiconductor manufacturers planned to purchase the majority of their equipment from Japanese suppliers (NRC, 1999). Given the heavy-handed role of Japan's Ministry of Trade and International Development in bringing new companies together to cooperate in targeting new markets and technologies, there were increasing cries in the U.S. for government action (NRC, 1999). Joint ventures, cooperative agreements, university-industry collaborations, and industry consortia all began to emerge during this period to fight what was seen as the Japanese threat (NRC, 1999). In January 1983, the Microelectronics and Computer Technology Corporation was formed and privately funded by 12 member companies. In 1984, the National Cooperative Research Act exempted research consortia from some antitrust laws and further facilitated collaborations. Perhaps most importantly, in 1987, 14 U.S. semiconductor companies joined a not-for-profit venture, SEMATECH, to improve domestic semiconductor manufacturing. In 1988, the federal government appropriated $100M annually for the next 5 years to match the industrial funding. With semiconductor manufacturing seen at the time as vital to the defense technology base, this money was channeled through DARPA (NRC, 1999).

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