Government Support of the Semiconductor Industry: Diverse Approaches and Information Flows

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Intensive research and development during the Second World War had resulted in new technologies such as radar, the proximity fuse, and the atomic bomb, all of which contributed to the Allied victory. The Cold War marked a new era in government funding for research and development, however, as new geopolitical pressures convinced military and civilian policymakers to maintain R&D expenditures at a level far exceeding that of the prewar years.[2] The majority of government research dollars after the war went to a small number of industries, most prominently aerospace and electronics [Mowery and Rosenberg, 1989, p.132], amply supporting both fundamental and applied research.[3]

Government funding of industrial R&D has received a great deal of attention from scholars in a number of disciplines. In particular, historians and economists interested in technological

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[2] The federal government contributed over half of all R&D funds until well into the 1970s. The military in turn accounted for the greatest proportion of federal R&D expenditures in industry for some time after the war. In only one year, 1966, did the military's portion of federal R&D spending fall below 50 percent [Mowery and Rosenberg, 1989, pp. 123-168].

[3] For the remainder of this paper the term "government" will mean the military and NASA, which were by far the greatest federal sources of R&D funding for the electronics industry.

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innovation have explored the questions of whether such funding has stabilized or distorted the general economy; how government funding affected industrial sectors and technologies; and whether some technologies and industries were favored over others. They have addressed questions about the efficiency and worthiness of federal R&D funding.[4] They have explored the effects of government funding on the direction of scientific inquiry, with debate between those who believe that the military orientation has diverted scientific inquiry from more socially valuable avenues and those who believe that no such "distortion" took place [Leslie, 1993; Forman, 1985; Kevles, 1990; Geiger, 1992, 1993].[5]

The Case of Microelectronics

The microelectronics industry in particular has attracted a considerable amount of investigative effort.[6] Most discussion of the effects of government support for this industry has taken place in the context of economic and policy arguments about the efficiency of industry and technology support programs. The consensus among industry analysts seems to be that the government, through its direct and indirect procurement policies, provided an early and price-insensitive market that promoted movement along the learning curve and allowed the industry to decrease prices as it learned how to

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[4]Mowery and Rosenberg [1989, Part III, "The development of the post-war system, 1940-1987"] provides a capsulation of these topics. Cohen and Levin [1989] provides an excellent summary of some of the relevant economics literature.

[5]For the "distortionist" view, see for example Leslie [1993] which uses MIT and Stanford University as illustrative of the effects that federal funding had on the direction of scientific inquiry in academia; see also Forman [1985]. The anti-distortionist camp includes Kevles [1990] and Geiger [1992, 1993, 1994].

[6] This industry is more commonly referred to in the 1990s as the semiconductor industry. In the 1950s, however, materials other than semiconductors were important, and "electronics" included tube technology: thus I will use "microelectronics industry."

make its products. These analysts credit the existence of the potential government market with inducing private investment in R&D. They also generally agree that government support of semiconductor research in university and industry laboratories contributed to the welfare of the semiconductor industry by building substantial bases of scientific and technical expertise there. The analysts conclude that the various federal agencies and institutions established an atmosphere conducive to technical innovation by requiring device and system performance beyond the state of the art.

Several studies of the microelectronics industry, however, make mention of another way in which government support of the industry has contributed to its success: "It is evident that government agencies have made a useful contribution to the diffusion of technological expertise in their role as information clearinghouses" [Golding, 1971, p. 334; Utterback and Murray, 1977, p. 34; Asher and Strom, 1977, p. 57].[7] This observation deserves more attention. By creating, supporting, and disseminating diverse approaches to technical innovation in semiconductor microelectronics, government agencies were extremely important in the overall development of micro electronic technology and thus also in the development of the microelectronics industry.

Diversity in approaches to technical advance, combined with flows of technical and scientific information, gains particular significance because of the complexity of microelectronic technology. The design and production of microelectronic devices involve chemical, mechanical, metallurgical, and photographic processes, each complex in itself. Furthermore, because microelectronics is a science-rich technology, it frequently benefited from, while not being

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[7] The original quotation is from Golding [1971, p. 334]; it also appears in Utterback and Murray [1977, p. 34].

subsidiary to, advances in scientific knowledge.[8] Although the desired end of technical innovation in microelectronics was usually clear--i.e., better performance according to commonly accepted criteria of what that constituted--the complexity of the technology and its use of knowledge from engineering, scientific, and empirical sources meant that the route to innovation was not always clear and that opportunities for innovation existed in many and diverse areas of research and engineering.

Herein lies the root of what is commonly referred to as "technical uncertainty." Nathan Rosenberg put it this way:

> The essential feature of technological innovation is that it is an activity that is fraught with many uncertainties. This uncertainty, by which we mean an inability to predict the outcome of the search process, or to predetermine the most efficient path to some particular goal, has a very important implication: the activity cannot be planned [Rosenberg, 1994, p. 93].

Technological complexity increases the variety and scope of areas of technical opportunity, multiplying the technical and scientific uncertainty. Rosenberg continues:

> No person, or group of persons, is clever enough to plan the outcome of the search process, in the sense of identifying a particular innovation target and moving in a predetermined way to its realization. . . [Rosenberg, 1994 p. 93].

In the context of the 1950s microelectronics industry, such uncertainty meant that no one firm could hope to perceive or tackle

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[8] Of course, R&D in science-rich technologies can also lead to the creation of new scientific knowledge. At different points in the history of such technologies science may be more or less important.

all of the areas worthy of investigation. In practice, managers of firms faced with choices among technological opportunities differed in their identification of particular innovation targets and thus induced differences in firms' R&D activities. This "heterogeneity of the human input"--that is, differences in "skills, capabilities, and orientations" [Rosenberg, 1994, p. 95]-- had a profound influence on the development of microelectronics technologies.

In circumstances of uncertainty and diversity in the perceptions of innovation targets, the importance of flows of technical information among innovators increased. The significance of these flows stemmed from and depended on the complexity of the technology; their existence, in turn, stemmed from and depended on social and economic as well as technical factors. In the case of early microelectronics technology, the U.S. government helped provide an environment conducive to both high flows of technical and scientific information and diversity in approaches to innovation.

Information Flows

In the early 1950s Bell Telephone Laboratories (BTL) was the world's richest source of technical and scientific information about transistors and semiconductor materials. BTL garnered the first military contract for R&D in transistor technology, a Joint Services contract issued in 1949 and extended consistently throughout the 1950s. The 1956 consent decree that finally settled a 1949 antitrust suit obligated AT&T, among other mandates, to distribute its patent information at reasonable cost to all interested parties. AT&T was already following a policy of making such information easily available to licensees. The legal power of the consent decree reinforced the firm's prior actions and ensured an ongoing and wide distribution of information [Smits, 1985, p. xii].

A provision of the Joint Services contract required BTL to hold a symposium in 1951 for invited military personnel and contractors. "We have been in touch with members of the three Military Departments regarding recent transistor developments in Bell

Telephone Laboratories," D. A. Quarles, a vice-president of Bell Labs, wrote to those nominated to attend. The developments "may have application in the field of military equipment," and so "it has seemed desirable to make this information available at the earliest feasible date to as many in military and in military contractor organizations as can be accommodated" [Quarles, 1951]. The attendees included personnel from government agencies, the military services, and researchers and executives from universities and leading industrial firms.[9] This event marked one of the first postwar government efforts to disseminate technical and scientific information about semiconductor devices and physics widely to industry and academia. The subsequent 1952 symposium on transistor science, engineering, and manufacturing for AT&T licensees further spread the technology.[10] The various means by which the government assured the distribution of Bell Labs' information were crucial early events in the history of this technology and industry.

Another feature of the 1949 Joint Services contract (and its extensions) was a final clause giving the government the right to distribute information produced under that contract.[11] Because Bell Laboratories carried on internally funded research alongside the military work, it often proved difficult to distinguish between these

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[9]The attendees included personnel from various military labs and commands; British, French, and Canadian representatives; researchers from 22 American universities; and personnel from 88 commercial firms. Some 119 defense contractors in all are listed as having sent representatives ["Transistor Symposium," List of Guests, 1951]. Note that this is a considerably larger number than attended the licensees' symposium held the following year.

[10]Attendees of the 1952 symposium included representatives from twenty-six domestic companies and fourteen foreign firms.

[11]For example, Article 51 of Contract #DA 36-039 SC-64618, which states in part: "The Contractor agrees to and does hereby grant to the Government . . . the right to reproduce, use and disclose for governmental purpose . . . all or any part of the reports, drawings, blueprints, data and other technical information specified to be delivered by the Contractor to the Government under this contract. . ." [AT&T Archives, 419 06 02 03].

bodies of knowledge. Nonetheless, information deemed to have been paid for by the government was subject to distribution to other defense contractors with an interest in microelectronics work, most often in the form of quarterly reports written by the researchers and submitted to the military sponsor.[12] "[S]oundly cursed by the developers who had to prepare them," these reports not only served the purpose of "keeping the military abreast of current development but also [of] teaching and stimulating other military contractors in industry and academia" [Andersen and Ryder, n.d, p. 186].

The military sponsors believed this dissemination of technical and scientific information important, and those who received the reports realized their value. The occasional tardiness of Bell Labs in submitting the reports, according to one company official, caused a "great delay in disseminating data which is first learned from a perusal of the reports," which in turn "prevent[ed] a more rapid utilization by industry of the advancements in transistor techniques developed by the Laboratories" [Morgan, 1956].

Bell Labs' quarterly reports were, in fact, widely distributed. Files in the AT&T archives are replete with requests for the reports, both from large firms such as Westinghouse and General Electric and from smaller firms including Baird Associates and Microwave Rectifiers [Case #26237-89]. BTL officials referred such requests to the Army Signal Corps, the contract administrator.

Such dissemination clauses were not exclusive to contracts with Bell Laboratories. For example, a 1954 Texas Instruments contract with the Air Force contained a clause allowing the quarterly reports to be "transmitted according to a distribution list furnished by

[12]Release of private information supplied to the government under contract was not allowed without permission from the producer. The contract system was, however, inherently "leaky." As Danhof [1968] notes, contract proposals from private firms may contain proprietary information. Such information risks becoming "part of the common stock of knowledge" [p. 249].

the Air Materiel Command" [Memo, 1955].[13] Similarly, Bell Labs itself received information produced under contract by other firms.[14] The dissemination of quarterly reports appears to have been widespread.

The AT&T consent decree assured that patents generated by BTL became easily available. For other firms, patents that resulted from military projects were subject to compulsory, royalty-free licensing for military purposes. Because most if not all microelectronics manufacturers were also military contractors, patents were not an effective barrier to the flow of information in the early years of the microelectronics industry.[15] This patent policy was part of a conscious government effort to promote the usefulness and efficacy of its research outlays. Just as industrial output had been crucial to the World War II effort, the federal government deemed "industrial preparedness" essential to victory as the Cold War threatened to heat up. The distribution of technical and scientific information was as essential to this plan as increased funding for R&D and for larger and more modern production facilities.

The electronics industry was a major beneficiary of industrial preparedness policies. The postwar military and its weaponry were increasingly reliant on electronics for communications, command and

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[13]The distribution list in this folder contains the names of firms small and large.

[14]For one example among many, BTL received General Electric's monthly reports on a transistor project from the Air Force [Newark Air Procurement District re contract # AF33 (600)-28956, letter to BTL, AT&T Archives, 419 06 01 12].

[15]For various reasons much that was patentable in the industry went unpatented. Asher and Strom [1977, pp. 27-28] contains a brief but effective explanation of the role of patents and patent policy in the industry. In the early years, firms frequently infringed each others' patents, in explicit recognition of the need for innovations on many different technical and scientific fronts. Patent holders calculated that prosecuting infringers would halt their own access to the infringers' innovations; as likely infringers themselves they were not interested in promoting prosecution. This dynamic changed as the technology matured, innovative opportunities became less common, and a few firms came to control crucial patents.

control, and computation. The rapid and wide deployment of electronics across the military establishment was crucial to the development of the so-called New Look military, dependent on superior intelligence-gathering and analysis, mobility, and weapons delivery. Advances in microelectronics technology depended on sophisticated science and engineering. Widespread access to scientific and technical information facilitated change. The industrial preparedness policy bore fruit in short order following the development of the transistor at BTL, as other firms made important technical and scientific contributions to the art.[16]

The services themselves had specific programs for disseminating information about their technical resources and needs. The Army, for example, established the Qualitative Development Requirements Information program "to alert industry to the unsolved problems confronting the Army," the Army Research Technical Studies program "to inform industry of the current research programs underway," and the Unfunded Study Program "to encourage industry to submit unsolicited proposals that might benefit the future development of Army materiel" [U.S. Army, 1963, p. 20]. The Air Force and the Navy organized similar programs, establishing information networks that served the needs of both the military and the microelectronics industry [Kleiman, 1966, pp. 179-180].[17]

Other government agencies also mandated dissemination of scientific and technical information. The National Aeronautics and Space Administration (NASA), for instance, born out of a ferment of political, military, ideological, and economic factors, from the outset

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[16]Raytheon, for example, quickly applied transistors to one of its products, hearing aids; Philco Corporation soon produced junction transistors by an electrochemical process; GE produced junctions by an alloying process. For Raytheon, see Scott [1974, pp. 206-207]; for Philco and GE, see Braun and MacDonald [1978, pp. 55-57].

[17]See also the Office of Naval Research publication, *Directory of Department of Defense Information Analysis Centers* (Washington, D.C., 1966), which lists some twenty-two official military sources for technical and scientific information.

included a division devoted to distributing technical information to industry.[18] The explicit purpose of NASA's Office of Technology Utilization was to see that technologies developed in the course of space-related R&D made their way quickly and efficiently into industry's hands. The agency now known as the Defense Technical Information Center (DTIC), whose predecessor had been formed at the end of World War II, collected reports and publications from defense contractors and distributed the data among them and other interested defense contractors.[19]

The government also contributed to the dissemination of knowledge in two ways beyond the formally mandated and contractual functions discussed earlier. The first derived primarily from the characteristics of military electronic equipment; the second was a product of the collateral effects of civilian advisory boards to the military.

State-of-the-art electronics grew increasingly complex in the 1950s. Early computers, an area of intense military interest, used circuits containing many thousands of components [Bashe et al., 1986; Cortada, 1993]. Requirements to transistorize, miniaturize, make more durable, and increase the performance of components added to the difficulty of developing reliable solid state circuitry. It was a technical task of the highest order.

The nature of the military's technological demands practically forced cooperation. Large and complex military systems were most often developed not by single firms but by coalitions of contractors

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[18]McDougall [1985, chap. 7, pp. 177-194] gives a good picture of the events and situations that led to the formation of NASA.

[19]This agency's original mandate, when it was the Armed Services Technical Information Agency, was to take charge of captured German technical documents and evaluate their possible military and industrial uses. Its name was changed after the war to the Defense Documentation Center and its mandate was expanded to be a central repository and clearinghouse for technical documents produced under military contract. The agency's name was later changed again to its present form.

and subcontractors. The Army Signal Corps' micromodule program, for example, funded from 1957 to 1963, involved a multiplicity of large and small microelectronics manufacturers. The compartmentalization of labor and the need to coordinate components' physical and performance parameters required participating firms to communicate technical and scientific information rationally and openly.[20]

Like the micromodule program, the Minuteman I and II missile programs required the participation and cooperation of many firms. Autonetics was the main contractor for the Minuteman guidance systems. The military considered the "team concept of Autonetics and its suppliers" used for Minuteman I so successful that it was adapted for Minuteman II [Asher and Strom, 1977, p. 22]. The list of Minuteman subcontractors included many of the industry's most prominent firms, which cooperated and communicated with each other. Fairchild Semiconductor Corporation (FSC), for example, consulted regularly with Autonetics on the design and performance of integrated circuits for Minuteman II [FSC, Stanford, 88-095].[21] Bell Labs did subcontract work and supplied technical information, and Motorola also participated in the effort [Asher and Strom, 1977, pp. 19-23]. Missile development was only one of many complex projects in the field of military and space electronics.

[20]RCA was the main contractor for this project. An executive of that firm stated, "this is a program which requires the skills of the entire electronics industry . . ." [Watts, 1959, p. 55]. Some articles mention up to one hundred firms participating during the life of the micromodule program; the Army's final report on the project lists seventy-one [Elders, Gerhold, Tenzer, and Azoff, 1964, Table 5, n.p.]. I thank Herb Kleiman for this document. The Diamond Ordnance Fuze Labs, an Army lab, and the Army Signal Corps' Laboratories at Fort Monmouth played major roles in the project. Information about this project is spread out among many sources in the trade and technical press. See, for example, Danko, Doxey, and McNaul [1959], Shergalis [1959], Granville [1960], Dummer [1967], Boehm [1962].

[21]Gordon Moore, a founder of Fairchild and its director of R&D from 1958 to 1967, states that the Minuteman program was very important for the success of Fairchild and the wider industry [Moore, interviews with author, February and June, 1994].

Solid-state conversions of computing, communications, control, radar, and guidance equipment were all under way.

The range of complex projects sponsored by the government had a lasting effect on the structure and practices of the microelectronics industry. The "commonality of interest among the contractors to the federal government," wrote two scientists closely associated with the industry, "promoted the high diffusion rate of new information in semiconductor electronics" [Linvill and Hogan, 1977].[22] The pattern of information transfer demanded by military contracts, combined with the pervasiveness of such contracts, established a pattern of communicating technical and scientific information among otherwise competing firms that persisted well into the 1960s [Holbrook, 1994]. Bell Labs' policy of information dissemination, as well as the general scientific ethos of free communication of information, also contributed to this behavior.[23] The complexity of the technology, however, reinforced the tendency.

Finally, the civilian boards that acted as advisors to the military in the postwar era contributed to the dissemination of information, though usually of a more general type. Prominent scientists from both the academic and the industrial spheres as well as business leaders from defense-related companies made up the

[22]Hogan was a Harvard physics professor who became Motorola's manager of semiconductor operations in the late 1950s, then headed Fairchild Semiconductor Corporation after Robert Noyce and Gordon Moore left that firm to found Intel. Linvill was a researcher at Bell Labs who went to Stanford University in the mid-1950s to take charge of its semiconductor physics program.

[23]Bell Labs director Mervin J. Kelly "recognized that the most rapid development of this new field would take place if, not one, but many companies participated in the work. To this end, he encouraged Bell Labs' first major Patent Licensing Symposium, as a means of disseminating knowledge . . ." [Fisk, n.d.]. The symposium "set a standard for the freer [*sic*] interchange of information in the semiconductor arena, a standard that prevailed for many years" [Smits, 1985, p. 30].

advisory boards.[24] Their regular meetings and communications among board members acted as conduits for information about defense research and procurement projects. The extent to which the advisory board network was used to disseminate information is difficult to ascertain, but certainly it did not slow the flow.

Many advisory board members had contributed their efforts to the military during the war; the advisory committees allowed the continuation of wartime contact among entrepreneurial scientists, business people, and the military personnel who granted and oversaw R&D and procurement contracts. William Shockley, for example, a co-inventor of the transistor, went into the transistor business for himself in 1955. He served at various times on advisory boards of all three military branches--participation that allowed him to fulfill his sense of patriotic duty, but also provided him with an inside channel for information about military needs and progress on others' projects. Shockley corresponded with many individuals within the military R&D establishment. For example, in 1957 he wrote to General J. D. O'Donnell, Chief Signal Officer, U.S. Army, concerning a meeting of one advisory board:

> . . . we discussed the future potential of transistors or other semiconductor devices. I indicated that I thought considerable insight into future performance could be had by theoretical studies now that many of the essential physical constraints are known [Shockley Collection, March 18, 1957].

He followed up this observation by soliciting such contracts for his firm. Similar correspondence went out regularly from Shockley's

[24]Members of the Air Force's Scientific Advisory Board, for example, included scientists and executives from many commercial firms, universities, and other federal agencies. See Sturm [1986].

firm to other military research agencies and laboratories [Shockley Collection, 90-117].[25]

Mutual laboratory and corporate visits also played a role in the dissemination of information.[26] Such visits cannot be attributed wholly to the existence of the advisory boards; they were (and are) part and parcel of the scientific world. The committees did, however, add to the possible paths in the network, usually on a high managerial level.[27] The growth of technology and business depends on the diffusion of information. As Diana Crane writes in her *Invisible Colleges*, "In technology . . . social interaction facilitates the diffusion of knowledge, but little is known about the nature of this type of social interaction" [Crane, 1972, p. 98].[28]

[25]For example, to people at ARDC, DOFL, China Lake, Wright-Patterson AFB, Ft. Monmouth, etc.

[26]The records of Shockley's firm contain many reports of such visits, as do records from FSC, BTL, and RCA. Fairchild Collection, Stanford Archives, 88-095; Shockley Papers, Stanford Archives, 90-117; AT&T Bell Labs Archives; and RCA Collection, Hagley Library. I thank Ross Bassett for providing me with the last item.

[27]This is an interesting area for further investigation. Previous study of scientific and technical advisory groups to the government has mainly concerned their roles in nuclear and scientific public policy. See, for example, Kevles [1979], which discusses the origins of scientific advisory boards between the wars as well as their postwar role. Little has been done on the implications for industry and technology of the communications and social networks fostered by the interactions of university and commercial researchers during and after service on military advisory boards.

[28]Collins [1974] examines in detail the social networks of scientists in various labs working on the development of a type of laser and the exchange of knowledge within that network. See also Taylor [1972].

Diverse Approaches

The development of complex, science-rich technologies depends on diverse approaches to technological advance operating within an environment of high information flows. As with the establishment of a formal information clearinghouse and the development of informal modes of information diffusion, the promotion of diversity derived from social, economic, and technological components.

The complex, intensive, and extensive nature of R&D on semiconductor devices and production processes presented rich opportunities for innovation: in the 1950s few technical areas were settled. On the scientific side, an ample supply of projects in chemistry, optics, physics, physical chemistry, metallurgy, and all their possible permutations awaited researchers. Tasks in equipment design and construction, materials processing, process control, and other engineering and mechanical tasks also needed attention.[29]

The immature state of the technology also allowed room for differences in perception about which approaches were worth pursuing. Deciding what research projects to take involved considerations of existing resources and expertise, strategic aims (both corporate and military), and perceptions of market potential as well as purely technical matters. Human factors, notes Rosenberg, also impinge on the problem: "Not only do human agents differ considerably in their attitudes towards risk; they differ also in their skills, capabilities, and orientations, however those differences may have been acquired" [Rosenberg, 1994, p. 95]. R&D managers, regardless of institutional venue, had different perceptions of the best approach (or approaches) to take, based on their commercial and scientific or technical experiences and expectations. This "heterogeneity of human inputs," combined with the uncertain state

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[29]Transistor technology did not stabilize until the mid-1960s with the emergence of the epitaxial planar diffusion/oxide-masked device and its eventual predominance.

of the technology, created a fertile field for diversity in approaches to innovation.

Government agencies also had reasons to pursue diverse approaches to technical advance in semiconductor technology. The three military branches and NASA, for example, had different needs, based on the types of equipment they required and the uses to which they put them, and those requirements conditioned the technological approaches they pursued. The Air Force valued small size, the Navy reliability, and the Army reliability combined with ruggedness and ease of repair [Kleiman, 1966, pp. 56-58, 180-184; Braun and MacDonald, 1978, pp. 92-95]; only the space program held miniaturization as a primary goal, with reliability a close second [Kleiman, 1966, p. 58].[30] Costs and concerns about supply convinced the services to support efforts to increase the mechanized production of electronic components and circuits [Latta, 1960; Bull, 1960; Hirshon, 1960].[31]

Interservice rivalry no doubt also played a role in the military's backing of alternative technological approaches, though it is difficult to document and should not be overemphasized in this case. Certainly such rivalry played a part in other fields with regard to both R&D and procurement,[32] but the existence and persistence of Joint Services efforts belies the preeminence of petty rivalries in

[30]For specific information on the Army's demands, see *U.S. Army Signal Corps Planning Guide for Long-Range R&D*, 1956, pp. 34-37, U.S. Army Military History Institute Archives, Carlisle Barracks, Pa.

[31]The military was not as concerned about initial procurement costs as it was about the maintenance costs, which for complex electronic equipment could be several times the initial costs. See Latta [1960], Bull [1960], and Hirshon [1960].

[32]See, for example, the discussion concerning the debate over control of the space program found in McDougall [1985, pp. 164-176].

semiconductor technologies.[33] Further, industry groups and the military both supported efforts to establish coherent and consistent standards for manufacturers of electronic components.[34]

Leaders of all the military branches were well aware of the many fronts on which technical progress had to be made if solid-state devices were to play the role the services envisaged for them. The diverse research areas outlined earlier all received support, sometimes even in a single contract. The 1949 BTL contract, for example, consisted of a number of specified "Tasks," which spanned science, engineering, and education efforts.[35] Joint Services Agency and Signal Corps contracts with industry backed "many different approaches for producing different components" [Utterback and Murray, 1977, p. 23].

Further, the military realized the benefits of widespread participation in research and development work and the importance that differences in approaches could make. The need for diversity in approaches is implicit in a statement from James Gavin, the U.S. Army Chief of R&D: "The total benefit to be derived from the ingenuity and know-how of American industry cannot be obtained

[33]The military branches' resistance to centralized control is well known. During the ongoing debate over the waste inherent in pursuing multiple approaches, all three branches expressed their revulsion for the "socialistic" aspects of centralized planning. See Starr [1955] and Komons [1966].

[34]The Armed Services Electronics Standards Agency, headquartered at Fort Monmouth, N.J., was a joint organization of the Army, Navy, and Air Force that established standards for components and materials. The Joint Electron Tube Engineering Council (JETEC), among other professional and industrial organizations, established standards to make component buying and circuit design easier for commercial concerns ["Grooming Transistors," 1957, pp. 66-70]. The National Bureau of Standards worked to establish measurement standards for the resistance of semiconductor materials, also in aid of industry. This work continued well into the 1980s [Kalos, 1983, pp. 91-106].

[35]There were originally five or six tasks, but contract extensions had expanded them to nine by 1959.

without the participation of small business as well as large. The Army is anxious to encourage small business interest in its R&D programs" [Gavin, in *Research and Development*, 1956]. The military had reached the same conclusion as had many industry participants: continued innovation in the microelectronics sector would require a broad array of approaches to achieve maximum progress.

Factors on the corporate side of the ledger helped create the diversity of approaches that the government supported. Different firms and individuals within firms possessed different perceptions of the needs of their customers and of their internal needs and capabilities. Some examples from efforts to integrate circuitry serve to illustrate this argument.

Approaches to Integration

As military and commercial applications of electronics increased, circuits became increasingly complex. Large circuits posed several interrelated problems. Reliability suffered; systems' failure rate, statistically and in practice, increased with the number of components, each of which had a specific failure rate. The sheer number of interconnections between components in complex circuits produced a larger reliability problem, because the connections, usually manually soldered or welded, were often imperfect or simply failed. Though the transistor may have removed some of the heat and power limitations of tube circuitry, it did little to resolve this problem, which J. A. Morton of Bell Telephone Labs came to call the "tyranny of numbers" [Morton, 1958]. Integration offered the possibility of alleviating this difficulty, as well as of miniaturizing the circuitry.[36]

[36]Miniaturization and reliability are positively correlated, though the direction of the causative arrow was (and is) unclear; for an extended discussion of the relationship between the miniaturization movement and efforts to increase reliability, see Kleiman [1966, pp. 54-77].

If the pressures to integrate were several, so too were the approaches to the problem in the mid-1950s. Solid-state electronic circuits used a variety of semiconductor materials such as germanium, silicon, and compound materials.[37] Firms designed, built, and sold both point-contact and various types of junction devices, using a wide range of production processes and techniques. Out of this diversity emerged the main approaches to integrating circuitry: modularization, thin films, hybrid thin-film/discrete circuits, "molecular electronics," and monolithic semiconductor circuits.

Although we know that the monolithic circuit eventually won out, in the mid-1950s that outcome was far from obvious. The uncertainty inherent in integration and the differing perspectives of the participants led to the pursuit of all the approaches. Each had its military champion: the Army backed modular approaches; the Navy thin films and hybrids; the Air Force ventured into the wild blue yonder of molecular electronics. Commercial firms also had specific reasons for backing one or another of these approaches.

Motorola, for example, displayed interest in integration beginning in the mid-1950s. Daniel Noble, the firm's chief scientist and head of its semiconductor division, advocated modularized circuit elements in 1954 [Noble, 1954]. Later in the decade, when integration pressures had increased, Noble wrote an editorial, "Necessity is the Mother," that advocated modules but also argued for continued thin-films research along with a longer-range outlook pursuing molecular electronics ideas [Noble, 1959]. Still later, Noble's successor as head of the semiconductor division wrote:

> In each case the technology you would choose depends on the particular circuit, and on the particular

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[37]Germanium was prevalent for active devices (transistors and diodes). TI had a monopoly on silicon devices for roughly two years following its introduction of the first silicon transistor in 1954. Compound semiconductor materials such as indium arsenide came under increasing scrutiny but proved recalcitrant. Attempts to make both active and passive components from tantalum also received a good deal of attention without much long-term success [Stone, 1962].

> application. Sometimes one technology is obviously superior to another; sometimes a combination of these technologies appears to optimize the system. We think that monolithic integrated circuits, hybrid integrated circuits, thin-film integrated circuits are all important, and that is why we have not concentrated on just one, but have developed in our facilities a capability in all fields [Hogan, 1963].

Motorola was a conservative firm that consistently emphasized giving its customers the best product for the purpose and price. Motorola hesitated to jump on any technological bandwagon, preferring instead to keep research efforts under way in several areas in order to best serve its clients. In no sense was the firm opposed to technical advance; its conservative strategy merely militated against the exclusive adoption of any one of the new integration technologies.[38] Thus the firm continued to advocate and make modular circuitry, an inherently conservative approach to integration, until well into the 1960s, by which time the monolithic integrated circuit was clearly becoming dominant.[39] Motorola's product strategy was conservative in other ways as well, emphasizing discrete components well into the 1970s, even as the company developed capabilities in integrated circuit technologies.

The modular approach attracted many other firms. A survey by *Electronic Industries* in 1962 found that thirty-five of the fifty-nine respondents (59 percent) were engaged in modular packaging activities. Thirty-four firms (57 percent) were pursuing thin-film

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[38]In fact, Motorola had established a research center in Phoenix in 1948 at the urging of Noble, whose wartime work and perceptions of postwar developments convinced him that future electronics would be dominated by solid state devices. The firm did not produce transistors for the commercial market until ten years later [Mueller, 1960].

[39]See *Motorola Engineering Bulletin*, vol. 13, no. 2, 1965, wherein articles advocate hybrid and modular circuitry.

approaches, whereas only fifteen (25 percent) were investigating monolithic approaches ["Microelectronics Today," 1962, pp. 92-99].[40]

Molecular electronics was Westinghouse's choice of technology for integration. In an attempt to move beyond existing technology and normal circuit design practice, they hoped to manipulate new and existing materials to impart to them inherent electronic functions. The Air Force was the main backer of this approach, funding it from 1959 until 1962 with a total of some $2 million [Braun and MacDonald, 1978, p. 95].

Westinghouse chose molecular electronics, according to one account, because the firm had fallen behind in conventional microelectronics technology and so wanted to "leapfrog" directly to the next generation of technology. Molecular electronics "was born in the firm's laboratories, partially from pure research efforts and partly from a response within Westinghouse to develop a new product to fill its semiconductor void" [Kleiman, 1966, pp. 188-189]. The Air Force, however, claims that the molecular electronics idea arose in 1953 within its laboratories at Wright Patterson Field [U.S. Air Force, 1965]. The Air Force chose to back this approach as a way both to distinguish its efforts from those of the other services and as a conscious move to incubate new approaches to microelectronic circuitry [Asher and Strom, 1977, pp. 14-17; Braun and MacDonald, 1978, p. 95].[41] Persistent enthusiasm for the concept within the Air

[40]These numbers clearly indicate that a number of firms were pursuing more than one of these approaches, as was the case with Motorola.

[41]Alberts [1962] states: "If the goal is still more miniaturization and reliability improvement, then a still more sophisticated approach must be found. It is the opinion of many Air Force members that this sophistication will be accomplished through the study of materials and phenomena with the express purpose of performing an equipment or circuit function in the simplest possible manner without reference to previous circuitry configurations or conceptions" (p. 235). Alberts was the research director of the U.S. Air Force Aeronautical Systems Division, Wright-Patterson Air Force Base, and was instrumental in most Air Force microelectronics efforts.

Force finally found a sympathetic ear at Westinghouse. Powerful allies in the defense establishment pushed the program and its potential benefits and urged its support [Kleiman, 1966, p. 202].[42]

The first molecular electronics contract bore a title relating to a crystal-growing project, though the research performed spanned several experimental areas, including semiconductor, magnetic, metallic, and crystalline materials, and combinations thereof, as well as investigations of various treatments that could alter the electronic characteristics of the materials.[43] The molecular electronics project as originally conceived bore little fruit. By 1962, Westinghouse had altered its use of the term to mean monolithic integrated semiconductor circuitry, thereby somewhat concealing the failure of the original concept [Stelmak, 1962].[44]

If modular approaches were conservative, requiring the adaptation of more or less standard components and processes, and the molecular electronics approach represented a blue-sky, radical mode of integration, then thin-film technology fell somewhere in between. Printed circuitry, with origins in wartime work at the Army's Diamond Ordnance Fuze Labs, utilized films of conductive materials applied to non-conductive substrates to provide electrical connections between active circuit elements such as vacuum tubes or

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[42]A main supporter was James M. Bridges of the Office of Defense Research and Engineering, DOD.

[43]Detailed technical information of the early phases of the molecular electronics program is elusive. Most references to it mention the goals of the project without specifying how these goals were to be obtained. See Haggerty [1964], "Special Report" [1962, p. 174], and "Electronics Goes Microscopic" [1959, p. 34]. This last article specifically mentions germanium and silicon as "the raw materials for [molecular electronics] devices," making it clear, however, that this was "mostly an accident" because these materials were then the best understood. The expectation was to be able to use a "wider variety of raw materials," including molybdenum, aluminum oxide, tungsten, tantalum, iron, nickel, and silicon dioxide.

[44]This article mentions only semiconductor materials. Stelmak worked for Westinghouse.

transistors. Printed circuitry reduced the failure rate of soldered wire connections and thus constituted an early attack on the "tyranny of numbers" problem [Danko and Gerhold, 1952]. The materials and techniques were simple, sometimes even crude. Conductive pastes silk-screened or stenciled onto ceramic, resin, or plastic boards formed connective lines. Basic passive devices such as resistors and capacitors were quickly developed.[45] The natural next step seemed to be the development of thin-film active elements [Lessor, Maissel, and Thun, 1964].

The relative simplicity attracted many firms, including some outside the established electronics industry. The materials employed in thin-film passive circuits--metals, ceramics, glasses, and plastics--were commonly used outside the electronics industry. Firms with experience in those materials became attracted to the potential for diversification into the microelectronics industry. Corning Glass Works, for example, long a supplier of materials for microelectronics and a maker of some passive components, had participated in the micromodule program as well. In the late 1950s, Corning managers contemplated a move into active electronic components, using thin-film integrated circuits as their entree [Boehm, 1962, p. 99]. Other firms both large and small also pursued this approach.[46]

Although thin-film research flourished in the early 1960s, success with thin-film active devices proved difficult to attain. As one article characterized the problems, "the major obstacle here is the

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[45]Active devices in a circuit, such as transistors and rectifiers, amplify or switch the current. Passive devices, such as resistors and capacitors, store or restrain the energy, adjusting it for feeding to an active device.

[46]In the 1965 *Industrial Research Labs of the United States*, thirty-one firms mention thin-film research activities. Many large firms, from diverse industries, are included in this group: AMF, Bendix Corp., Ford Motor Co., RCA, Sylvania Electric Products, General Electric, Martin Marietta, Motorola, Raytheon, Texas Instruments, United Aircraft, Xerox. Smaller firms such as Stupakoff Ceramic and Manufacturing of Latrobe, Pa., and Halex Inc., founded in 1959, also sought to move into thin-film electronics. See also Gartner [1959], *Business Week* [May 5, 1962, p. 116], Rasmanis [1963], and Dummer [1967].

difficulty in depositing thin single crystal layers of semiconductors, or in depositing a polycrystalline film so thin and pure that recombination at dislocations and grain boundaries does not deteriorate the current amplification" [Gartner, 1959, p. 42].[47] The growing superiority of monolithic integrated circuits by the mid-1960s hastened the demise of thin-film projects.

Hybrid circuits used thin-film passive elements and conventional semiconductor active elements such as transistors and diodes. This approach did not, as a rule, emphasize microminiaturization; proponents mainly sought low price and high reliability. By using two well-known technologies, hybrid circuits suited many applications that did not require high standards of compactness but did need reliability and ease of manufacture. Hybrid circuits posed none of the circuit performance limitations that accompanied other integration techniques. IBM, for example, used hybrid circuits until well into the 1970s for exactly such reasons [Bashe et al., 1986, pp. 406-415; Pugh, Johnson, and Palmer, 1991, pp. 48-112].

Monolithic integrated circuits, the last approach, consist of a piece of semiconductor material, most commonly silicon, treated to construct transistors, diodes, and passive elements within (or upon) it. This approach, the most common today, was invented almost simultaneously in 1959 by Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor Corporation. These two individuals and firms possessed the skills necessary to make such devices, though they differed in important ways. Although still a relatively small firm in 1959, Texas Instruments occupied a leading position in the microelectronics industry. Active in many areas of semiconductor research, including all of the approaches to integration described, the firm partook extensively of military R&D funds. By

[47]Gartner mentions research being done in this area as early as 1959 but unfortunately does not mention any firms by name. The author, however, was Chief Scientist, Solid State Devices Division, Electronic Component Research Dept., U.S. Army Signal Research and Development Laboratory, so the work mentioned may have been taking place either there or under military contract. He went on to become manager of Semiconductor R&D at CBS Hytron in 1960.

contrast, Fairchild was only two years old in 1959. Though immediately successful, it was small and stayed focused on a single type of product. Noyce's conception of the integrated circuit came directly out of Fairchild's experience making silicon transistors [Wolff, 1976; Noyce, 1977]. Texas Instruments' integrated circuit came from Kilby's experiences making transistors at Centralab, a division of Globe-Union [Wolff, 1976, p. 46; Kilby, 1976]. The differences between the two correlated with the differences in technological approaches the two firms used. Noyce chose silicon as his material and a method of interconnection made possible only by use of planar construction, a Fairchild invention. Kilby used germanium and interconnected his device using wires.[48] Both, however, cited the importance of the "broad base of semiconductor technology" in the United States, as well as "the importance of early contributions by many people in their own companies and in the rest of the industry" [Wolff, 1976, p. 53].

The military very quickly supported the monolithic idea. Texas Instruments received a development contract from the Air Force in 1959. Fairchild resisted taking direct military support for its R&D, though the government remained its largest customer for some time [Wolff, 1976, p. 53].[49] By the mid-1960s monolithic integrated circuits had achieved widespread acceptance despite their performance limitations, and by 1970 the other approaches, though not dead, had lost much of their research appeal.

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[48]Kilby's prototype used these materials; I do not mean to imply that Texas Instruments went forward strictly according to Kilby's model.

[49]Most of Fairchild Semiconductor's products went either directly or indirectly to the military, and thus its success was dependent on military monies. In 1959 John Carter, president of Fairchild Semiconductor's parent firm, Fairchild Camera and Instrument Corp., stated that the semiconductor division's business was 80 percent military and 20 percent commercial [*Palo Alto Times*, October 9, 1959; clipping in diary of William Shockley, Stanford University Archives].

Conclusion

Government support for the microelectronics industry in the 1950s consisted of more than simply providing a market for the industry's output and building a trained personnel pool. The government established an atmosphere conducive to innovation on a wider base than the lure of large procurements and R&D contracts. It took concrete steps to establish and encourage the transfer of technical and scientific information among otherwise competing firms, with profound consequences for the development of microelectronics technology. The government was not the sole source of such information flows; AT&T's policies of openness as well as the scientific ethos of free exchange of information must also enter the equation.[50] Nevertheless, the actions of various government agencies served to expand and reinforce existing information exchange networks. Diverse information moved over these channels: both scientific and technical, it concerned not only transistors or any one device, type of device, process, or approach, but many.

The problem of integrating circuitry certainly benefited from the pursuit of diverse approaches. Looking backward, we can clearly see the contributions of the other approaches to the success of the monolithic integrated circuit. Thin-films research, for example, advanced the art of putting down delicate but precise layers of metals, ceramics, and semiconductor materials, all of which play a part in modern integrated circuits. Similarly, the far-reaching molecular electronics program, though it failed to meet the goals established for it, nonetheless contributed knowledge of materials and processes that found a place in more successful technologies. Such technical and economic failures are more than simply wrong paths or dead ends; they play an important role in technological development, particularly in complex, science-rich technologies such as microelectronics.

[50]Other conditions under which otherwise competing firms might exchange information informally are modeled in von Hippel [1986].

The case of the microelectronics industry has other implications as well. The business environment during the Cold War was marked by the intermingling of the military and its money, the varied motivations of industry participants, and technological uncertainty. Companies with different histories and thus different perspectives chose differently how, when, and in which areas to use government support. The military branches with their own differing sets of interests and needs chose to support different technologies. Each technological approach was able to satisfy some sets of perceptions and received ready support from both sides. Thus, various approaches to circuit integration were supported at the confluence of organizational perceptions and aims. Some historians observe that military support at least greatly affected, if it did not actually pervert, the direction of academic research [Leslie, 1993; Forman, 1985]. There is little doubt that commercial electronics firms, on the other hand, largely maintained control of their research agendas and profited significantly from their association with the military.

The existence of diverse interests made the military and business environments of the late 1950s well-suited to the development of microelectronics technology, but it also complicates the task of delineating the technology's history. It is not simple, or perhaps fruitful, to point to a single factor that "explains" the success of the microelectronics industry or even the failure of individual firms or projects. Each of the factors described can itself be broken down further, thereby further complicating the analysis. Simplifying it by ignoring any of the factors, however, risks missing important nuances in the development process.

Neither should we overlook the importance of the demands of the technology itself. Microelectronics demanded inputs not only from the scientific realm but also from engineering, empirical tests, and "black magic."[51] The technology required both scientific research

[51]This term was used by semiconductor researchers to cover the vast areas of physical and manufacturing processes that they did not fully understand. It covers a large body of tacit knowledge.

and extensive development efforts. Technological development remains inadequately "unpacked," especially but not exclusively by economists, whose

> dominant view of the innovative process is still overly Schumpeterian, in its preoccupation with discontinuities and creative destruction, and its neglect of the cumulative power of numerous small, incremental changes [Rosenberg, 1994, p. 126].[52]

The incremental changes in early microelectronics accumulated from the pursuit of diverse approaches to problems, with the pursuers connected by both formal and informal channels of information exchange.

Examining the role that the government played in the creation and support of diverse approaches to technical advance and of avenues of knowledge transfer can also provide some insights into the more general theme of industry and technology policy. In the case of microelectronics, the government does indeed have a bad record of picking technology "winners," if by winners we mean silicon-based monolithic integrated circuits, the mainstay of today's industry.[53] Indeed, picking the eventual "winner" would have been prescient; very few of those intimately involved with the technology at the time managed to do so. From the wider perspective offered by this paper, however, the government, even in its support of economic "losers,"

[52]There are certainly exceptions to this. Nelson and Winter [1982], though they adopt a Schumpeterian (or neo-Schumpeterian - p. 39) perspective, are sensitive to the cumulative and evolutionary aspects of innovation. Their interest in "an explicit theory of industry behavior" rather than in "individual firm behavior" (p. 36), however, allows them to theorize about firms' routines without having to consider the historical origins of those routines.

[53]Many analysts of the government's role in the technology and industry make this point [Asher and Strom, 1977; Kleiman, 1966; Golding, 1971, for example]. None explore in any depth the contributions of the "losers" the government picked, however.

did much to advance the winning technology and thus the industry. By supporting a diverse set of projects and by either demanding or encouraging the sharing of the knowledge produced thereby, the government helped to create a successful technology and industry. The important spillovers from these government-sponsored projects were not products but technical and scientific information. And if, as Nathen Rosenberg states, technological innovation is so uncertain that it cannot be planned, then encouraging diversity is the best "planning" we can do [Rosenberg, 1994, p. 93].

Diversity and dissemination are thus powerful tools for industrial policy. Whether they do or will work as well with other technologies and in other industries remains to be seen. The conditions that reigned during the development phase of integrated circuitry, a Cold War fed by both an arms and a space race, no longer exist. Urgent economic and competitiveness problems do exist, however, and technology resides at the center of many of them. Furthering diversity and dissemination seems only prudent.

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