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**From Spin-Off to Spin-On:
Redefining the Military's Role in
Technology Development**

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Introduction

Soon after the U.S. military's smashing, quick victory in the Persian Gulf War, George Bush went to speak with the people who had built the Patriot missile at Raytheon's defense plant in Massachusetts. "What has taken place here," he assured them, "is a triumph of American technology; it's a triumph taking place every day, not just here at Raytheon, but in the factories and farms all across America where American workers are pushing forward the bounds of progress, keeping this country strong, firing the engines of economic growth. What happens right here is critical, absolutely critical, to our competitiveness, now and into the next century."

In essence, the President gave the right speech in the wrong plant. Far more critical to American competitiveness than what happens at Raytheon's missile plant may be what has already happened at another Raytheon plant, where the company still produces the Amana radar range, an early version of the microwave oven. A commercial "spin off" from U.S. military technology, microwave ovens are now a high volume consumer electronics product for both Japanese and South Korean firms whose commercial sales far outstrip Raytheon's sales of radar ranges. The growing sophistication of microwave technology continues to increase its use in both military and civilian applications. But it is the employees of East Asian electronics firms, not the employees of Raytheon, who are the most practiced at making it.

From microwave ovens to microchip computers, military and civilian initiatives now represent two distinct approaches to developing advanced technology. While the United States has traditionally used military projects to generate technological breakthroughs, other countries, most notably Japan, now use commercial markets to accomplish the same ends--faster, with higher standards for product reliability, and at significantly lower cost. In areas where no high-volume civilian markets yet exist--gallium-arsenide components, massively parallel computing--technical spin-offs from the U.S. military sector still have time to redound to the competitive benefit of America's civilian firms. But in a world where foreign producers of military-relevant commercial technologies emphasize speed in both product development and technology implementation, time is a luxury the United States may no longer be able to afford.

There are many cases in which the spin-off model has worked well to establish U.S. leadership in both military and civilian applications. In the semiconductor industry, as our first case study will show, military policy certainly helped to clear a path for

commercial market penetration. The government required a domestic second source on all Pentagon contracts and provided loan guarantees for constructing new production facilities. Both actions effectively lowered entry barriers and diffused innovative technology among competing firms. Military procurement then provided an extremely effective initial launch market, fueled at premium prices.

Yet even when America's technology edge was at its sharpest, the spin-off strategy sometimes faltered. Our second case study details the ways in which military-specific performance requirements cramped the civilian diffusion of Air Force-sponsored computer control technology for machine tools, encouraging the development of an over-specialized civilian industry that was commercially vulnerable to foreign competitors. In this instance, spin-off proved to be a clumsy mechanism for moving innovative technology from military to civilian markets in a timely and competitive fashion.

By the late 1970's such divergence in performance requirements for military and civilian products had already become a more general phenomenon. More importantly, American efforts to advance the core technologies on which both sets of product applications rested had diverged--unnecessarily--as well. The spin-off approach had created a domestic military-industrial enclave, inhabited by firms that organized themselves for the sole purpose of marketing to the Pentagon; this left them with business strategies and market antennae that were unresponsive to the strains of commercial competition and insensitive to the drift of civilian technological innovation.

Pentagon planners responded with a set of projects designed to extract military-specific applications from state-of-the-art commercial producers. Two are examined here--the military's effort to develop very-high-speed integrated circuits (VHSIC) and the Pentagon's Strategic Computing Program (SCP) sponsored by DARPA, the Defense Advanced Research Projects Agency. In the end, the esoterica of military performance requirements, combined in some cases with wasteful attempts to overcome unnecessary security restrictions, succeeded only in reinforcing the bifurcation that still characterizes the American technology base. New military applications were in fact created, sometimes in a way that genuinely advanced the technology base, but those advances were few in comparison to the rapid-fire achievements emerging simultaneously from the civilian sector--not only at home but, increasingly, abroad. In the end, the military programs did not impede such advances so much as bypass them altogether.

It is often the case now that technology diffuses from the civilian sector to the military, rather than the other way around. Spin-on, an alternative approach to building military and commercial applications off a common technology base, has emerged most fully in Japan, where militarily-relevant sub-system, component, machinery and materials technologies are rehearsed and refined on high-volume commercial applications. Much of that work occurs in the context of government-orchestrated research projects whose explicit object is the creation of commercial technology applications.

In this new competitive context, spin-off and spin-on must be regarded as different approaches to the problem of organizing and financing the development of advanced technology. As the stories we are about to tell suggest, spin-off can still work under specific circumstances. In areas where no significant civilian competition has yet been established, for example, spin-off can work to diffuse innovative technology from the military to the civilian sector. It only works, however, because American firms in the civilian sector have time, in these cases, to appropriate the economic benefits from their own applications.

But now as in the past, spin-off can also be a source of competitive disadvantage. Over-reliance on spin-offs hurts civilian economic competitiveness when commercially-irrelevant performance requirements are already designed into the technology that diffuses from military to civilian producers. Even when divergent specifications are not a problem, generic military-sponsored technology with commercial applications may simply be too slow to diffuse to civilian producers--particularly in instances where alternative civilian applications of the same underlying technology have already appeared on the market.

This latter scenario is increasingly likely to be the case. Even more disturbing, for those concerned with American security, are the military uses to which such foreign-born commercial technology can increasingly be put. Many of America's most vaunted weapons--from the AmRam missile to the M-1 tank--could literally not be built without commercially-developed Japanese machine tools. Without commercially-derived Japanese components for their radars, America's F-16 fighter pilots could never find their targets. Regardless of its impact on the nation's commercial competitiveness, the military's traditional approach to developing advanced technology may already be obsolete for its own purposes.

Yesterday's Spin-Offs: Both Sides of the Story

Case studies of previous Pentagon attempts to involve commercial firms in military technology development are a useful way to gauge the relative potential of a spin-on strategy against the spin-off strategy that has characterized U.S. technology policy since the end of the Second World War. Looking back over the years, it is evident that some of these attempts have been successful, and some have not. In some instances, the military's technological purpose was achieved and the competitive position of civilian industry was strengthened. In other instances, the commercial impact of military projects was negative or, at best, negligible. By examining all three types of cases, we can identify the circumstances that have been associated historically with each outcome.

Solid-State Transistors and Integrated Circuits. The development of solid-state microelectronics--transistors and integrated circuits--is cited often as a case of positive commercial spin-off from the military sector, and with good reason. It is important to note, however, that even at its most successful, spin-off still represented a second-best solution to the problem of promoting the commercial technology base. As early as 1958, the military's emphasis on military-specific devices conflicted with the commercial interests of the Bell System, causing Bell executives to worry that military design specifications might be undermining the production efficiency of Bell's manufacturing arm, Western Electric.

Nevertheless, military procurement provided a crucial launch market for untried semiconductor technology, fostering a market environment that encouraged entrepreneurial risk-taking. Concerned that the military might classify its technological breakthroughs, Bell Labs rushed to make its semiconductor innovations public and its patents marketable. The Pentagon also required a domestic second source for its semiconductor purchases, a requirement that further lowered market-entry barriers and accelerated the diffusion of technological advances. The early, military-structured market environment clearly promoted the development of a strong, independent semiconductor industry in the United States. The differences between this case and the case of numerical controls (which follows) illustrate the key role played by the technical requirements of the highest-volume user--then and now--in determining the prospects for successful spin-offs.

1948 had witnessed a fortuitous match of military needs and commercial objectives. Driven by the rigorous performance requirements of its military mission, the

Army Signal Corps had institutionalized the goal of miniaturizing electronic communications gear. At the same time, scientists at Bell Telephone Laboratories were searching for an effective solid-state amplifying device to replace mechanical relays in telephone exchanges. Both objectives were satisfied initially by the invention of the point-contact transistor, announced by Bell Labs in 1948.

The Army Signal Corps' effort to miniaturize military electronics had begun in the late 1930's and culminated in the first "walkie-talkie." Although it represented a major improvement in battlefield communications, the six-pound, football-sized, two-vacuum tube transmitter-receiver with separate telephone handpiece was too bulky for many military operations. Miniaturization thus received special emphasis in the Signal Corps' long-range R&D plans after the Second World War. Working with the electronics industry, the Signal Corps soon developed an automatic soldering system (Auto-Sembly) to facilitate the mass production of miniaturized components.¹

One week before the first public demonstration of the transistor, Bell Labs held a special briefing for the military services. Scientists at the Labs had long been aware of the military's interest in their work. They waited as long as possible to disclose their results for fear that disclosure of the transistor to the military prior to a public announcement would lead to severe restrictions on its commercial use or outright classification in the name of national security.²

As expected, researchers from the Signal Corps Labs were immediately enthusiastic about the new device, sensing its amenability to the Auto-Sembly technique. Within months, the Corps had set up a small manufacturing facility to produce test devices. By June of 1949, the military had convinced Bell to sign a contract for the study of potential applications. This contract eventually resulted in the first published research on the applications of transistors to digital computers.

¹ For a detailed account of the Army Signal Corps' involvement in the development of the transistor, see T.Misa, "Military Needs, Commercial Realities, and the Development of the Transistor, 1948-1958," in M.R. Smith (ed.) Military Enterprise and Technological Change: Perspectives on the American Experience (Cambridge, MA.: MIT Press, 1985).

²R. Levin, "The Semiconductor Industry," in R. Nelson (ed.) Government and Technical Progress: A Cross-Industry Analysis (New York: Pergamon Press, 1982), p. 58. Bell's continuing policy of swift public dissemination of its research results was influenced primarily by the anti-trust suit that the U.S. Department of Justice initiated against AT&T in 1949. According to the terms of the 1956 consent decree that eventually ended the suit, Bell Labs continued to act as a sort of national research facility, disseminating basic solid-state technology and channelling the energies of commercial semiconductor firms to the search for broader applications.

Although this first military contract supported general application and circuit studies, Bell's second military contract specified that materials, services, and facilities be devoted to studies of military interest. Internally, Bell began to coordinate its transistor development with military requirements. The military market was important because the Bell System was having trouble introducing transistors into the telephone system. The phone system could only introduce transistors as older vacuum-tube equipment was retired; this process was to take more than a decade. Also limiting non-military markets at first was the high cost of solid-state devices. The first transistorized hearing aid sold for \$229.50. Raytheon's 1955 transistor radio was considered a luxury item and retailed for \$80.³ Unlike radio listeners and hearing aid users, the military could subsidize the technology's development costs in order to increase the scale of production.

Military money underwrote the construction of a huge Western Electric transistor plant in Pennsylvania; Raytheon, RCA, and GE also benefitted from military support. In return for guaranteed government purchases (at premium prices) of a part of their output, the companies agreed to build production capacity 10-12 times greater than that needed to supply the government's current demands. This request apparently related to the military's constant interest in "surge capability," that is, the capacity to ramp up expanded production rapidly in case of a wartime emergency.⁴ In peacetime, however, the resulting excess production capacity created a further incentive for the industry develop new commercial markets.⁵

In addition to subsidizing plant construction and enlarging production capacity, military contracts facilitated the dissemination of information about the underlying technology to potential users outside of the military services. As required by its second military transistor contract, Bell Labs held a symposium on transistor applications in September of 1951. The lectures and demonstrations were attended by over three hundred representatives of academia, the military services, and the electronics industry. Each participant received a 792-page volume of the symposium proceedings; in addition, the military services distributed an additional 5500 copies at government expense. A second conference in April 1952, funded by Western Electric but held at the urging of the military services, resulted in two fat volumes detailing the scientific fundamentals of

³ Misa (1985), pp. 274-275.

⁴For more on the notion of surge capability, see S. Melman, Profits Without Production (New York: Alfred Knopf, Inc., 1983).

⁵M. Borrus, Competing for Control: America's Stake in Microelectronics (Cambridge, MA.: Ballinger, 1988), p. 66.

transistor technology. Thus, at a time when Western Electric, AT&T's manufacturing arm, was only just beginning transistor production for trial use in AT&T's civilian long-distance telephone system, Bell Labs was already disseminating the transistor technology that "enabled all [Western Electric] licensees to get into the military contracting business quickly and soundly."⁶

Military support for transistor research at Bell rose from a small level in 1950 to 50 percent between 1953 and 1955. By the mid-1950's Bell Lab scientists had made two major technological advances. Advances in solid-state theory and metallurgical techniques made possible the creation of "junction" transistors, which were mechanically less fragile than point-contact transistors. In addition, the invention of the diffusion technique for manufacturing transistors made possible the mass production of devices that could amplify high frequencies.

As basic transistor development proceeded, however, the applications desired by military users began to diverge more and more from the types of applications that Bell Lab scientists envisioned for use in the public telephone network. Aside from bulkiness, additional problems with military communications equipment had been revealed during the war. Walkie-talkies had failed when confronted with extremes of temperature--freezing in the arctic, moisture and corrosion in the jungle. They had also failed when subjected to other rigors of battlefield use, including shock, vibration, and sudden changes in temperature. These problems led the military services to prefer devices constructed from silicon instead of germanium. The ambient temperature in jet aircraft and guided missiles, for instance, often exceeded the 75° C. maximum operating temperature of germanium transistors; silicon devices would continue to operate in environments as hot as 150° C. The expansion of the Navy's nuclear fleet and the Air Force's plan to develop a nuclear-powered plane also increased the importance of silicon's inherent resistance to radiation.

The U.S. military's interest in silicon transistors set the American industry on a development trajectory that was decidedly different from the germanium-based development trajectories that were being explored in Europe and Japan in the 1950's. That interest also influenced the structure of the emerging U.S. semiconductor industry:

⁶ Bell Telephone Lab Report, 1957, cited in Misa (1985), p. 268. See also Borrus (1988), p. 61.

it enabled the primary manufacturer of silicon transistors, Texas Instruments, to carve out an early niche in the emerging semiconductor market.⁷

In addition to promoting silicon over germanium, military requirements fostered attempts to exploit certain physical properties of semiconductors that were not likely to find wide commercial application. As important as miniaturization, heat resistance, and resistance to radiation all were for military users, for example, what the Signal Corps most wanted was a transistor capable of amplifying very high frequency (VHF) signals for computers and communications equipment. This led the military services to prefer *diffused* or "*intrinsic barrier*" devices to the point-contact and junction devices most commonly used in Bell System applications. (Bell researchers had invented diffused devices in 1954 in a project supported by a Signal Corps contract). Intrinsic barrier devices were difficult and expensive to manufacture, but they were used in several military applications. Bell needed only small numbers of diffused germanium devices, but missiles required high-switching speeds and so the military demanded large numbers of diffused transistors, mostly silicon.

Flush with new R&D funds due to the massive rearmament effort that followed the Korean War, the Signal Corps actively pushed the electronics industry to provide transistors in the form that it wanted. In 1956 the Corps placed \$15 million worth of development contracts for work on diffused devices, the largest amount of R&D funding ever awarded up until that time. The stated purpose of these awards was to "make available to military users new devices capable of operating in the very high frequency (VHF) range which was of particular interest to the Signal Corps communications program."⁸

⁷ Military patronage of relatively new and innovative semiconductor producers, such as TI, grew in significance because most established commercial electronics producers were slow to recognize the revolutionary potential of solid-state technology. The early transistors were less reliable than vacuum tubes and more expensive; except for its adaptation to the manufacture of hearing aids, for which its compactness made it especially well-suited, the transistor was not regarded as an economical substitute for vacuum tubes for most consumer electronics products. According to Braun and MacDonald, "Despite the early interest in the transistor as a better valve [tube], the transistor was so radically different from the valve in the way it worked, in the way it could be manufactured and sold, and in its apparent potential, that it could not be comfortably accommodated within the existing electronics industry without changes that that industry was then unwilling or unable to make." E. Braun and S. MacDonald, Revolution in Miniature: The History and Impact of Semiconductor Electronics (London: Cambridge University Press, 1978), p. 69.

⁸ William R. Stevenson, "Miniaturization and Microminiaturization of Army Communications--Electronics, 1946-1964," U.S. Army Electronics Command, Fort Monmouth, New Jersey, Historical Monograph I (unpublished manuscript, 1966), pp. 125 and 130. Cited in Misa (1985), p. 282.

Although the awards provided the military services with the devices that they wanted, it became increasingly clear that the main trajectory of commercial development was headed in a different direction. By the end of 1958 Western Electric had manufactured 171,000 diffused transistors. All of them were destined for military applications and none for internal consumption by the Bell System. Internal memoranda circulating around Bell Labs at the time suggested that big military projects were taking too many Bell engineers away from non-military development work. What is more, Bell telephone network applications were beginning to outsell military applications--two large telephone projects accounted for over one million transistor sales in 1956, when total military sales were expected to be only 175,000.⁹

Still, the military services continued to affect the specific forms that the developing technology would take. A rapid proliferation of transistor types appeared in the 1950's as different firms investigated various potential applications (and different development trajectories). Because it was too hard to integrate several transistor types into a single system, the military pushed for standardization. The Signal Corps had already sponsored a conference in mid-1953 aimed at standardizing the operating characteristics of transistors (by contrast, the British semiconductor industry remained without national standards until the 1960's).¹⁰ In 1957, the head of Bell Lab's Nike missile development project came up with a plan to standardize and expedite the development of transistors needed specifically for military systems. The so-called "preferred" devices--both germanium transistors for high-frequency needs and silicon to meet high temperature requirements--were all diffused.¹¹

Military spending on microelectronics research continued to expand into the 1960's, but it was military *procurement* that did the most to shape both semiconductor technology and the entrepreneurial dynamic of the American semiconductor industry. During the 1950's the military services had supported a number of research projects aimed at the development of new microelectronic components for the next generation of military weaponry (radar, fire control systems, and missile guidance systems). All of these projects, including Tinkertoy and Micromodule, were dominated by established electronics firms, such as General Electric, Hughes, and RCA; none of them were

⁹ Misa (1985), p. 283-284.

¹⁰ Misa (1985), p. 285.

¹¹ A year later Bell Labs developed a similar "preferred-device" program to streamline transistor development for Bell System applications.

successful.¹² The first integrated circuit was eventually demonstrated in 1958 by Texas Instruments, which had developed its device without direct research and development support from the military. Nevertheless, Jack Kilby's own account of his invention confirms that Texas Instruments had solely military applications in mind when research into the new devices began.¹³

Once the integrated circuit had become a reality, the armed forces spared no effort to support its further development. Between 1959 and 1962, TI, Westinghouse, and Motorola received \$9 million worth of military contracts for further work on integrated circuits. TI alone received a \$1.15 million, two-and-a-half-year development contract in mid-1959, followed by an additional \$2.1 million contract, awarded at the end of 1960, to come up with special manufacturing equipment and production techniques that would allow the new devices to be mass produced.¹⁴ Despite the military's early enthusiasm, however, commercial producers remained wary. As late as 1961, many scientists in industry and academia still voiced doubts that integrated circuits would work in actual electronic equipment and systems.¹⁵ Having decided in 1958 to employ integrated circuits in the guidance system of the Minuteman missile, the Air Force was concerned to alleviate these doubts once and for all. Under Air Force sponsorship, a small digital computer was introduced into the Texas Instruments production program. Two demonstration computers were built: one was made with discrete semiconductors and required 9000 individual components; the other performed identically, but contained only 587 integrated circuits.

By providing an initial market at premium prices for major advances, military purchasers accelerated their introduction into use.¹⁶ As production for the military

¹² In fact, most of the early military contracts went not to innovative start-ups like Transitron, Motorola, or Texas Instruments, but to established suppliers of soon-to-be-outmoded vacuum tubes, like General Electric, Western Electric, Sylvania, Raytheon, and RCA. As late as 1959, the big firms were awarded 78 percent of the federal research money for learning how to manufacture cheaper, more reliable transistors, even though they accounted, at that time, for only 37 percent of the transistor market. Braun and MacDonald (1978), p. 81, cited by Robert DeGrasse in J. Tirman (ed.) The Militarization of High Technology (Cambridge, MA: Ballinger, 1984), p. 91. Also mentioned in R. Reich, The Next American Frontier (New York: Times Books, 1983), pp. 190-91.

¹³ Evin (1982), p. 61.

¹⁴ N. Asher and L. Strom, The Role of the Department of Defense in the Development of Integrated Circuits (Arlington, VA: Institute for Defense Analysis, 1977), pp. 4, 17. Also cited in M. Borrus, J. Millstein, J. Zysman, U.S.-Japanese Competition in the Semiconductor Industry (Institute of International Studies, University of California, Berkeley, 1982), p. 17.

¹⁵ Asher and Strom (1977), p. 17.

¹⁶ This point has been made by J. Utterback and A. Murray, The Influence of Defense Procurement on the Development of the Civilian Electronics Industry (Cambridge, MA: MIT Center for Policy Alternatives,

proceeded, producers accumulated experience. Experience soon translated into lower unit costs. Within a few years, the price of a given device was typically low enough to spawn civilian applications, first in industry, then in consumer products. Nevertheless, the most significant consequence of early military interest in integrated circuits occurred on the supply-side. In the era of the vacuum tube, the manufacture of electronic components was dominated by large, multidivisional producers of electronic systems; as semiconductor technology gained ground, this continued to be the case in Western Europe and Japan. In the United States, by contrast, military procurement decisions effectively created an independent segment of "merchant" semiconductor suppliers, that is, companies organized to manufacture semiconductors primarily for sale on the open market, instead of primarily for internal use.¹⁷

As early as 1959, new merchant producers accounted for 69 percent of all semiconductor sales to the military services (a figure which translated to 63 percent of total semiconductor sales). Texas Instruments and Fairchild, the two new firms which had pioneered the development of integrated circuits, became major military subcontractors--TI was charged with providing integrated circuits for the Minuteman II missile guidance system while Fairchild got the NASA contract to provide an IC-based guidance computer for the Apollo spacecraft. The rapidly increasing utilization of integrated circuits by both NASA and DOD enabled other emerging suppliers, such as Motorola and Signetics, to intensify their focus on IC production.

Besides its contribution to the creation of a flexible and highly-independent production network for semiconductor components, military policy also encouraged the widespread dissemination of basic technological information among competing companies. The Department of Defense typically obtained a comprehensive license of free use for any patentable products or processes that had been developed by private contractors with military funds (and for military use). This meant that firms that had developed commercially-relevant innovations in the context of a military project had to

1977), page 3; I. Magaziner and R. Reich, *Minding America's Business* (New York: Harcourt, Brace, Jovanovich, Inc., 1982), and Borrus (1988), p. 69-70.

¹⁷This point has been emphasized previously by Borrus, Millstein, and Zysman (1982), p. 15: "The shift to the transistor and ultimately to the integrated circuit reshuffled the composition of the leading component manufacturers. Few of the leading producers of the electron tube managed to retain their component market positions in the new technologies. In this reshuffling process, *defense and aerospace procurement created a market incentive for entrepreneurial risk-taking and thereby helped to spawn an independent sector of semiconductor component manufacturers* (emphasis added)." Their assessment of market share "reshuffling" is based on Ian Mackintosh, *Microelectronics in the 1980's* (London: Mackintosh Publications, Ltd., 1979) p. 66, table II.

share information about the innovation with any firm or individual who subsequently worked on a government contract or a private project supported by government funds.¹⁸ Moreover, the Defense Department typically followed a strategy of "second-sourcing," that is, requiring at least two independent sources for a component before it could be included on an approved list for use in military equipment. Second-sourcing also encouraged rapid technological diffusion; co-contractors often shared patent rights, drawings, photomasks, and manufacturing know-how.¹⁹

In sum, instead of yoking suppliers to military users and thus privileging the development of military-specific forms of IC technology, military policy contributed to the development of an industrial structure that would soon prove highly beneficial to the rapid commercialization of IC technology. The very independence of the semiconductor merchants encouraged them, indeed *required* them, to pursue all possible alternative applications of the underlying technology. As new companies entered the industry (Signetics, Siliconix, General Microelectronics, Molectro), total IC production mushroomed, growing from about \$4 million in 1963 to roughly \$80 million in 1965. IC prices fell (from \$31 in 1963 to below \$9 by 1965), emboldening older producers of electronic systems (RCA, Sylvania, Motorola, Raytheon, Westinghouse) to move into volume production.²⁰ As civilian computer and industrial applications increased in the mid-1960's, the importance and influence of military procurement declined rapidly. Government (mostly military) users accounted for 100 percent of the U.S. market for IC's in 1962, 55 percent in 1965, and 36 percent in 1969. By 1978, government's share of the U.S. IC market hovered around 10 percent.²¹

Numerical Controls. Although some tension had developed between military-specific performance requirements and the commercial interests of fledgling semiconductor producers (particularly Bell Labs), military procurement policy--price subsidies, second-sourcing--had simultaneously fostered the development of an entrepreneurial industry and a commercial market that soon outpaced the military market

¹⁸ Borrus (1988), pp. 71-72.

¹⁹ D. Webbink, "Staff Report on the Semiconductor Industry" (Washington, D.C.: Federal Trade Commission, Bureau of Economics, 1977), p. 97. Cited in W. Baldwin, The Impact of Defense Procurement on Competition in Commercial Markets (Washington, D.C.: Federal Trade Commission, Office of Policy Planning, 1980), pp. 55-56.

²⁰ Borrus (1988), p. 72.

²¹ 1962 figure from J. Tilton, International Diffusion of Technology: The Case of Semiconductors (Washington, D.C.: The Brookings Institution, 1971), cited in Borrus (1988); Other figures from U.S. Department of Commerce, "Report on the Semiconductor Industry" (1979) (also cited in Borrus, 1988) and interview materials.

in both size and technological sophistication. Spin-off was successful because Pentagon policy ultimately allowed the technical needs of high-volume commercial users to dominate the market and drive the technology.

Military intervention did not always have such salutary commercial effects, however, even in the heyday of successful spin-offs. Military performance requirements and procurement practices actually impeded the civilian diffusion of innovative computer control technology for machine tools. The commercial industry's over-reliance on Pentagon-sponsored technology and funding--an over-reliance on military spin-offs--ultimately created a domestic military-industrial enclave. The enclave came to be inhabited by firms whose market antennae and technological requirements were fine-tuned to the specialized needs of military users. This rendered them increasingly out of tune with the needs of a (potentially) much larger civilian market.

Between 1949 and 1959, when the Air Force discontinued its formal support for software development, the military spent at least \$62 million to research, develop, and diffuse numerical control technology, most of it originating at MIT's Servomechanism Laboratory.²² In this initial phase of the technology's evolution, Air Force performance specifications defined a unique development trajectory for Servo Lab engineers, a trajectory linked to end-use requirements that were well beyond the standard needs of most potential commercial users. Specific performance requirements for four- and five-axis machining stemmed from the Air Force's need to fashion large, structurally complex metal parts (integrally-stiffened wing sections, variable-thickness skins, etc.) out of tricky materials, as components for high-speed aircraft and missiles.²³ The Air Force also wanted a system that could be rapidly re-programmed in an emergency over commercial communication channels. Together these requirements led Servo Lab engineers to create a software system known as APT (Automatically Programmed Tools) that was at once

²² D. Noble, "Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools," in A. Zimbalist (ed.) *Case Studies on the Labor Process* (New York: Monthly Review Press, 1979), p. 25. MIT was chosen because of the Servo Labs experience with automated gunfire control systems.

²³ Although military and managerial preferences for top-down control certainly may have played an important role in promoting acceptance and enthusiasm of NC and APT, technological development was driven primarily by the Air Force's specific end-use requirements. Noble acknowledges, in fact, that "Air force performance specifications for four- and five-axis machining of complex parts, often out of difficult materials were simply beyond the capacity of either record-playback (or manual) methods." Noble (1979) p. 29.

universally applicable and infinitely adaptable, with the additional ability to control the motions of a cutting tool along five axes in unbounded space.²⁴

The same technical characteristics which made this trajectory so appealing to military users rendered the system overly expensive and sophisticated for most commercial applications. The dominant programming approach followed by early industrial users of numerical control involved the development of a two-dimensional executive routine, or "pilot program." The pilot program could then be programmed to select from a library of subroutines, coordinating them for more complex three-dimensional work. APT transcended the coordination problem by creating a more fundamental system that recognized general categories of cutting problems which could then be particularized for individual surfaces and dimensions. The fact that APT was more fundamental, more flexible and adaptable, and more capable of growth than the subroutine approach also meant that it was more cumbersome and more prone to error; APT required the largest available computers and the most highly skilled mathematicians to program them.²⁵ In brief, the system possessed all of the features required to meet the specialized demands of the Air Force and "none of the generality and simplicity required to express economically and in an easily learned way the huge range of everyday machine operations."²⁶

A military-specific development trajectory for numerical control technology pervaded the American machine tool industry on the demand side because large-scale military development efforts occurred during the period of the technology's initial creation, when interest among commercial firms was distinctly cool. The *entrenchment*

²⁴ Faced with a cutback in Air Force support for the numerical control project in the Spring of 1955, Servo Lab engineers, who had developed a program for two-dimensional two-axis machining, pushed for new funding to complete work on a "more efficient" program suited to three-dimensional, three-axis machining. Hoping to reap the benefits of its previous investment, the Air Force obliged, but not before defining an even more forward-looking standard for five-axis control. See D. Noble, Forces of Production: A Social History of Industrial Automation (New York: Oxford University Press, 1984), pp. 140-141.

²⁵ Noble (1984), p. 143.

²⁶ E. Sabel, Work and Politics: The Division of Labor in Industry (Cambridge: Cambridge University Press, 1982), p. 69. Or, in the words of Harley Shaiken, APT, for most metalworking operations, was the equivalent of "using an M-1 tank to drive to work." H. Shaiken, Work Transformed: Automation and Labor in the Computer Age (New York: Holt, Rinehart, and Winston, 1984), p. 100. A 1981 survey indicated that "while 46% of the firms with a large number of NC machine tools (11 or more) used APT, only 15% of the firms with a medium number (5-10) and 13% of the firms with a small number (less than 5) used APT" P. Ong, NC Machine Tools," in Industry and Trade Strategies, "Programmable Automation Industries," Report to the Congressional Office of Technology Assessment [contract no. 333-2840, April (1983). Nevertheless, because the initial use of APT created a set of software programs that could not be easily translated, it continued to be the *de facto* industry standard long after a new generation of simpler programming languages became commercially available.

of that trajectory, or the creation of a *military-dominated trajectory* among the industry's core firms occurred on the supply side, in the subsequent organization of the supplier network and its characteristic relationships with large machine tool users. The argument, in brief, is that military involvement promoted the creation of a specialized production infrastructure for NC tools. A combination of industry structure and military policy turned the attention of NC tool suppliers away from the work of developing potential applications for high-volume producers of consumer durables.

Between 1949 and 1953, MIT and the Air Force both mounted massive campaigns to interest commercial machine tool builders in numerical control; in all that time, however, only one private company, Giddings and Lewis, Inc., was interested enough in the new technology to invest even a portion of its own funds. Partly in response, the Air Force set about creating both a market and a set of preferred suppliers for numerical controls. The Air Force paid for the purchase, installation, and maintenance of over 100 NC machines in prime contractor's (mostly aerospace) factories and funded training programs to teach the contractors how to use the new technology. In 1955, promoters of the technology successfully changed the specifications for stockpiling machine tools in the Air Material Command budget allocation from tracer-controlled to numerically-controlled machines.²⁷ The results were impressive: between 1951 and 1957, private research and development expenditures in the U.S. machine tool industry multiplied eight-fold, most of it underwritten by the aerospace industry.²⁸

The Air Force practice of "seeding," that is, placing NC tools with selected users, provided these large-scale, technologically advanced firms with a dominant hold on the NC segment of the machine tool market.²⁹ Combined with the high price and technical complexity of the tools, Air Force contracts worked to restrict the market to the aerospace industry and similar specialized uses. In the absence of an industrial policy that might have identified and perhaps even subsidized commercial alternatives, the industry's emphasis on meeting military-related needs made sense from a business perspective.³⁰ High-level aircraft industry executives desired cost-plus contracts with the

²⁷ As Noble states, "Companies that wanted military contracts were compelled to adopt the APT system, and those who could not afford the system, with its training requirements, its computer demands, and its headaches, were thus deprived of government jobs." Noble (1979), p. 28.

²⁸ Noble (1979), p. 25; A. DiFilippo, Military Spending and Industrial Decline: A Study of the American Machine Tool Industry (New York: Greenwood Press, 1986), p. 57.

²⁹ Over the years, in fact, the Air Force made a practice of favoring with its contracts the core of suppliers it created in the 1950's, many of whom remained major producers into the 1990's (Ong, 1983).

³⁰ For a similar view, see D. Collis, "The Machine Tool Industry and Industrial Policy, 1955-82," in Spence and Hazard (eds.) International Competitiveness (Cambridge, MA.: Ballinger, 1988), p. 108.

Air Force and overcame initial resistance within their companies to the exclusive use of APT.³¹

Beyond making APT the industry standard, military policy actively narrowed the diffusion of the latest APT developments to its own clients, after which the developments became in effect proprietary information that could be used to commercial advantage. On-going APT research was shifted to the Research Institute of the Illinois Institute of Technology (IITRI) in 1961, where it has been guided by a consortium composed of the Air Force, the Aircraft Industries Association (AIA), and major suppliers of machine tools and electronic controls. Membership in the consortium is expensive, beyond the financial means of most companies in the metalworking industry. Access to APT systems has thus been effectively restricted to AIA members (including Boeing, Lockheed, Convair, Chance Vought, Bell, Martin, McDonnell Douglas, North American Aviation, Northrop, Republic, and United Aircraft) and affluent non-members such as General Motors, Goodyear, IBM, and Union Carbide. Within user plants, APT information is treated as proprietary; programmers must sign out manuals for use at the plant (they cannot take them home), and they are forbidden from discussing the technology with people outside the company.³²

Over time, the military-dependent environment fostered close collaborative ties between large users and the largest machine tool suppliers, further promoting specialized end-use developments and the establishment of advanced manufacturing systems geared toward the particular needs of large aerospace firms. The standardization around APT, promoted by the Air Force, inhibited for more than a decade the development of simpler programming languages which might have made contour programming more accessible to smaller machine shops. When breakthroughs in programming methods (for example, the creation of MDSI's Compact II) and computer design (for example, the invention of microprocessors) made it possible to develop low-cost, mass-produced NC tools in the 1970's, most large American tool makers simply had too little experience with consumer durables producers to detect and exploit the un-met commercial demand for such equipment. Smaller tool suppliers who did attempt to adopt numerical controls for commercial applications were forced into a position of technical dependence on the large firms that had controlled the development of APT.

³¹ Within many of these companies, engineers had developed in-house languages to program N/C equipment; they were typically less flexible than APT, but simpler to use.

³² Noble (1979), note, pp. 27-28; Noble (1984), p. 209.

By contrast, Japanese machine tool makers benefitted from their close ties to major *industrial* users and were able to shift more rapidly to the mass-production of smaller NC equipment in the early 1970's.³³ Many Japanese machine tool firms are owned wholly or partly by their major industrial customers; Toyota Koki is partly owned, for instance, by the large automobile manufacturer Toyota. According to Friedman (1988), many small and medium-sized tool producers are also linked to large industrial users through geographic concentration; within these clusters, groups of tool firms specialize in tools needed for specific industries and benefit from long-term production and sub-contracting arrangements. These ties have presented Japanese tool makers with an opportunity to develop numerical control technology with an array of commercial end-uses in mind. Aided with finances and technical expertise from other divisions of their corporate groups, Japanese tool producers were quicker than their American and European counterparts to introduce microprocessors into their NC control systems in the early 1970's. In all, Japanese production of low-cost numerically-controlled lathes and machining centers increased ten-fold between 1970 and 1979.³⁴

Japanese successes in this sector were due in part to government policy; for the most part, however, Japanese tool makers have benefitted from their close ties to large industrial users, who provided an early and consistent source of alternative development trajectories for NC technology.³⁵ MITI sponsored the rapid diffusion of NC technology throughout the Japanese economy, operating through a set of regional technical assistance centers--financed from bets collected on company-sponsored bicycle races--to teach small and medium-sized metalworking shops how to use NC tools.³⁶ But private Japanese firms began as early as 1955 to apply work done by MIT's Servo Lab engineers, and the first computer-controlled NC tools developed in Japan were shown at an international exposition in 1958.³⁷

³³ For more description and analysis of the Japanese machine tool industry, see Ong (1983), E. Vogel, *Comeback: Building the Resurgence of American Business* (New York: Simon and Shuster, 1985), M. Fransman, "International Competitiveness, Technical Change, and the State: The Machine Tool Industry in Taiwan and Japan," *World Development* 14 (12) (1986), D. Friedman, *The Misunderstood Miracle: Industrial Development and Political Change in Japan* (Ithaca, N.Y.: Cornell University Press, 1988), and Collis (1988).

³⁴ Ong (1983).

³⁵ Fransman (1986), p. 1383.

³⁶ Ong (1983).

³⁷ Vogel (1985), p. 80; and Fransman (1986), pp. 1382-83; both cited in D. Gold "The Impact of Defense Spending on Investment, Productivity, and Economic Growth," (Washington, D.C., Defense Budget Project, 1990), p. 52.

By the late 1970's, market share figures were revealing the damaging consequences for U.S. competitiveness of a military-dominated development trajectory for the technology of numerical control. By 1979, more than two decades after the technology became commercially available, only 2 percent of all machine tools used in the United States were numerically controlled; in 1978, only 3.7 percent of the metalworking equipment used by the U.S. machine tool industry itself was numerically controlled.³⁸ Although the total number of NC machine tools almost doubled between 1978 and 1982, imports as a share of the value of U.S. consumption rose from a little over 23 percent in 1980 to more than 35 percent by 1983, almost 90 percent of them from Japan.³⁹ In 1984, two-thirds of the numerically-controlled turning machines and three-quarters of the NC machining centers installed in U.S. firms were bought from foreign firms.⁴⁰ During the first seven months of 1985, more than 50 percent of all NC tools used in the United States came from overseas.⁴¹ The fall of the dollar after early 1985 slowed the competitive decline of U.S. producers somewhat, but the industry's long-term prospects are still considered precarious.

Spin-Off Today: The Dilemmas of "Dual Use"

In the late 1970's the spread of America's competitive troubles to such high-tech sectors as semiconductors and computer-controlled machine tools was still typically linked to Japanese protectionism rather than a decline in native technological prowess. Still, many analysts found the trend unsettling. Toward the end of the Carter Administration, a series of apprehensive research reports appeared from various outposts of the military establishment.⁴² The reports decried the deteriorating state of the nation's "defense industrial base," the industrial infrastructure which formed, according to

³⁸ Melman (1983) pp. 8-10.

³⁹ U.S. Department of Commerce, International Trade Administration, "A Competitive Assessment of the U.S. Manufacturing Automation Equipment Industries" June, 1984, pp. 22-25; pp. 36-37.

⁴⁰ U.S. Department of Commerce, U.S. Industrial Outlook 1985, (Washington, D.C.: 1985), Chapter 21 "Metalworking Equipment" p. 21-7.

⁴¹ "Machine Tools Industry Update," Prudential-Bache Securities, November 4, 1985, prepared by Christine Chien and Laura Conigliaro.

⁴² Defense Science Board Task Force Report on industrial competitiveness (Chairman, Richard Furhman), November 21, 1980; the Air Force Systems Command statement on defense industrial base issues (General Alton Slay), November 21, 1980; House Armed Services Committee Industrial Base Panel Report, "The Ailing Defense Industrial Base; Unready for Crisis" (Chairman, Richard Ichord), December 31, 1980. See also the influential book by Jacques S. Gansler, former Deputy Assistant Secretary of Defense and Assistant Director of Defense Research and Engineering: The Defense Industry (Cambridge, Mass.; MIT Press, 1980).

proponents, the civilian backbone of the nation's military posture.⁴³ In response, military planners began to work with their consultants in private industry to devise technology development projects that would involve commercial firms in planning, promote the use of commercially-available components (whenever possible), and subsidize the commercial development of basic "dual use" technologies that were expected to find wide application in both the military and commercial sectors. Two Pentagon projects, the Very High Speed Integrated Circuit (VHSIC) program, and the Strategic Computing Program (SCP) are illustrative of this approach. Both ran throughout much of the 1980's and have had a negligible impact on the commercialization of their constituent technologies.

Unlike the Pentagon's earlier semiconductor and numerical control efforts, VHSIC and SCP occurred when a set of commercial development trajectories for semiconductor and computing technologies were already well-established, not only in the United States but also in Western Europe and Japan. In an environment where multiple development trajectories already existed, military-specific end-uses rapidly became the *raison d'être* for the military projects. Despite their best efforts to promote "dual-use," Pentagon planners were ultimately (and perhaps appropriately) most interested in inducing leading-edge commercial producers to supply military applications that none of their commercial customers wanted.

VHSIC. In early 1977 President Jimmy Carter, Secretary of Defense Harold Brown, and Brown's director of research, William Perry agreed to push for the rapid development and deployment of the cruise missile. Characterized by its reliance on state-of-the-art electronics to steer close to the ground--thereby avoiding enemy radar--the cruise missile (like other precision-guided munitions) epitomized the strategic use of U.S. technology to offset Soviet numerical superiority in conventional long-range weaponry. Nevertheless, the cruise missile's apparent dependence on research breakthroughs in microelectronics and materials science soon underscored a concern that had already been growing within the Pentagon about the so-called "insertion lag." The term refers to the

⁴³ Emerging as it did in an increasingly conservative political climate, the DIB concept gave politically-tenable expression to an interventionist enthusiasm somewhat sheepishly shared by many supporters of Ronald Reagan. Industrialists, venture capitalists, university presidents, Wall Street bankers, and significant segments of the military establishment all stood to benefit from increased government assistance to high technology industry. Nonetheless, most were tied to an ideological stance that denied the legitimacy of state action in the economy. Accordingly, these diverse economic interests began to coalesce around the political cause of strengthening the "defense industrial base." For more details, see D. Dickson, *The New Politics of Science* (Chicago: University of Chicago Press, 1988).

amount of time that elapses between the commercial availability of an integrated circuit and its utilization in a weapons system. By the late 1970's, the insertion lag had reportedly reached a span of twelve years. An intelligence report in the fall of 1977 suggested, further, that the U.S. military's lead over the Soviets in microelectronics had dwindled to substantially less time than that.⁴⁴

Through the rest of 1977 and 1978, Perry and a handful of DOD officials set about establishing a major university-based research program in very-high-speed integrated circuits (VHSIC), solid-state components which are essential to the operation of cruise missiles and other precision-guided munitions. VHSIC was to emphasize advanced computer and data-processing architecture, new approaches to computer-aided design of complex circuits, and research into the materials and physical processes needed to achieve submicron geometries—all areas at the cutting edge of technological development. The program was in many ways a response to the demands of military users who had become increasingly frustrated over their inability to convince commercial semiconductor producers to develop custom chips for military applications.⁴⁵ With less than 10 percent of the semiconductor market (compared to more than 50 percent up through the mid-1960's), producers of military systems had little financial leverage left with which to entice innovative semiconductor firms into doing military contract work.⁴⁶ "We were forced to use decade-old microelectronic technology," complained one Pentagon official, "while Atari games were using the latest."⁴⁷

Commercial semiconductor producers understandably preferred to focus their financial and design resources on commodity chips that were likely to command lucrative large markets, such as those used in personal computers and video games.⁴⁸ By the mid-1970's commercial semiconductor technology had advanced several years ahead of concurrent developments in the military sector, and cutting-edge developments were clearly being driven by the needs of large commercial users.

⁴⁴ Dickson (1988).

⁴⁵ Committee on Assessment of the Impact of the DOD Very High Speed Integrated Circuit Program, An Assessment of the Impact of the Department of Defense Very High Speed Integrated Circuit Program (Washington, D.C.: National Academy Press, January 1982), p. 6, and interview materials.

⁴⁶ By the late 1970's only five percent of the industry's R&D expenditures were being funded through military contracts. Ruth Davis, IEEE Computer, (July 1979); Committee on Assessment (1982), p. 22; and Semiconductor Industry Association estimates.

⁴⁷ Quoted in Julian, High Technology (May 1985), pp. 49-57.

⁴⁸ The military services were more interested in high-speed than large-scale processing.

Appearing before the Senate Armed Services Committee in 1979, Perry made no secret of the Pentagon's desire to regain control of the technological agenda in microelectronics by promoting the concept of dual use. VHSIC's planners intended to "direct the next generation of large-scale integrated circuits to those characteristics most significant to defense applications," he testified. VHSIC would, furthermore, "insure that the U.S. maintains a commanding lead in semiconductor technology and that this technology will achieve its full potential in our next generation of weapons systems."⁴⁹

With the merchant semiconductor producers' research and production efforts geared overwhelmingly toward industrial and consumer markets, Pentagon planners recognized that merchant decisions to participate in VHSIC would be treated as a matter of corporate strategy, not national security. Each firm's decision to participate would be based primarily on a belief that VHSIC objectives matched the objectives of in-house technology development, and a conviction that participation in the program would accelerate in-house progress toward meeting *common* developmental goals.⁵⁰ An important, though secondary, spur to participation was the notion that VHSIC participants would be the first to profit from any commercial spillovers that might arise from VHSIC technology.⁵¹

Spillovers and military/civilian complementarity were the core objectives of a dual-use strategy. Indeed, the identification of potential spillovers and complementarities was a major goal of VHSIC planners, who recognized early on that "VHSIC could not be sold to industry on national interest alone or even in large part."⁵² An early planning document stated that VHSIC technologies "must be consistent with mainstream industry efforts" and that "program goals must be consistent with the industry learning process."⁵³ Following the first rule of a dual-use strategy, VHSIC planners sought and incorporated

⁴⁹ Testimony of William J. Perry to the Senate Committee on Armed Services, U.S. Congress, Hearings on Department of Defense Authorization for Appropriations for Fiscal Year 1980, 96th Congress, first session.

⁵⁰ Interview materials. For a similar finding, see G. Fong, "The Potential for Industrial Policy: Lessons from the Very High Speed Integrated Circuit Program," *Journal of Policy Analysis and Management* 5 (2), (1986). Many semiconductor firms--most prominent among them, Intel--saw no valuable complementarities or spillover potential in VHSIC, and so chose not to participate. In all, ten merchant semiconductor firms eventually sought participation in the VHSIC program.

⁵¹ Interview materials and materials supplied by the VHSIC program office.

⁵² M. Yoshino and G. Fong, "The Very High Speed Integrated Circuit Program: Lesson for Industrial Policy," in B. Scott and G. Lodge (eds.) U.S. Competitiveness in the World Economy (Boston: Harvard Business School Press, 1986), p. 182.

⁵³ materials supplied by the VHSIC program office. Also cited in Fong (1986).

substantial advice from private industry about appropriate technical goals and organizational features for the program.

In particular, the Pentagon's Advisory Group on Electron Devices (AGED) provided a critical institutional link between government and private industry during VHSIC's planning.⁵⁴ Comprised of industrial and academic specialists, AGED sponsored two Special Technology Area Reviews in September and November 1978. Thirteen companies were invited to make formal presentations on prospective VHSIC technology: Fairchild, GE, Hughes, IBM, Motorola, National Semiconductor, Raytheon, RCA, Rockwell, Sandia, Texas Instruments, TRW, and Westinghouse.⁵⁵

Concerned to rein in military-oriented technical goals that far outstripped the near-term needs of commercial users, industry representatives convinced VHSIC planners to focus solely on silicon devices, rather than on both silicon and gallium arsenide. They also convinced them to scale back the program's interim goal for feature size from submicron line widths to a more reasonable 1.25 micron widths after the program's first three years. Industry input was also instrumental in increasing the program's development support for computer-aided design (CAD) tools.

In addition to affecting the program's technical end-use requirements, AGED reviewers addressed the area of supply-side organization. AGED reviewers evolved the notion of multifirm "teaming." The idea of teaming VHSIC users and suppliers was a departure from the Pentagon's usual practice of making awards to numerous individual contractors. Though substantial consultation had occurred in the past between the military equipment and military components divisions of companies working on procurement contracts, collaboration between the research and development divisions of different firms was not a widespread practice. AGED reviewers thought this should change. In order to improve communication between systems experts in user firms and component experts in supplier firms, companies were asked to apply for VHSIC contracts in teams. Each team would include the manufacturer of a military system and a merchant

⁵⁴ See G. Adams, *The Iron Triangle: The Politics of Defense Contracting* (New Brunswick, N.J.: Transaction Books, 1982), especially pp. 165-173, for more on the many advisory boards that link the broader scientific and industrial communities to the U.S. Department of Defense. My thanks to Glenn Fong for pointing out the importance to VHSIC of the 1978 AGED reviews.

⁵⁵ The sessions were also attended by representatives of Bell Labs, Cal Tech, Carnegie Mellon, Clemson, Cornell, Fairchild, Hewlett-Packard, the Institute for Defense Analysis, Jet Propulsion Labs, Johns Hopkins, Lincoln Labs, MIT, RCA, Research Triangle Institute, SRI, Stanford, Tektronix, Texas Instruments, TRW, the University of California at Berkeley, and Westinghouse.

semiconductor firm, plus companies specializing in other technically-relevant areas such as design, processing, packaging, and testing.

Participating semiconductor firms expected to benefit commercially from anticipated advances in the areas of computer-aided design (CAD) and lithography. CAD techniques seemed especially suited to the strategic needs of commercial producers, since their wider introduction would have the effect of "shifting some of the design burden from the device manufacturer to the user, [thus allowing] semiconductor companies to reduce the amount of engineering time they must commit to new product development."⁵⁶ Commercial spillovers were anticipated primarily in the area of process technology. The development of a CMOS (complementary metal oxide semiconductor) production line for VHSIC circuits was expected, for example, to advance the process technology for other CMOS applications in the fields of microprocessors and telecommunications.⁵⁷

In practice, the notion of complementarity between civilian and military goals was manifested in the way most participating firms organized their VHSIC work. In most cases, VHSIC activities were fused with each firm's mainstream development and production efforts, rather than being isolated in separate military divisions. For example, VHSIC work at Motorola, National Semiconductor, and Texas Instruments proceeded under the direction of the same corporate vice presidents who were responsible for overall semiconductor R&D. TI did not separate VHSIC and commercial VLSI work at all, while VHSIC engineers at Motorola and National were drawn from, or worked closely with, engineering personnel that had been involved in each company's on-going VLSI efforts.⁵⁸

Yet the project's efforts to promote the idea of dual use seemed to bear little fruit; only one VHSIC chip had actually been built into a military system by the end of 1987.⁵⁹

⁵⁶ *Aviation Week and Space Technology*, February 16, 1981. cited by Brueckner (1984), p. 29.

⁵⁷ D. Moore and W. Towle, "The Industry Impact of the Very High Speed Integrated Circuit Program: A Preliminary Analysis," (Arlington, VA.: Analytic Sciences Corporation, 1980).

⁵⁸ Interview materials. Fong (1986) reports similar findings. This practice was not universal, however. L. Brueckner and M. Borrus, "Assessing the Commercial Impact of the Pentagon's Very High Speed Integrated Circuit Program," (BRIE Working Paper 5, University of California, Berkeley, November, 1984) found, in one instance, a VHSIC contractor that kept VHSIC and VLSI work strictly separate for legal reasons, even though the work itself was substantially identical.

⁵⁹ The process of getting a chip approved for military use still takes so long and requires so much bureaucratic red tape that the chips slated for use in a weapons system are often obsolete by the time the system makes it from design to production. Military screening often takes more than a year and is responsible, by some accounts, for over half the cost of a typical military-qualified chip. The long lag time

This means that, at best, the "insertion lag" had been reduced from twelve to seven years. Honeywell, a major VHSIC contractor, moved its chips from production on six-inch diameter silicon wafers to a four-inch diameter line, citing lagging demand for Phase I chips. What is more, many *commercially*-developed chips from the VLSI generation could meet all of the technical parameters that were said to define military-sponsored VHSIC chips (a geometry of 1.25 microns or less, ability to run at 25 mega-hertz or more, with a total density of 500 billion gate-hertz per square centimeter).⁶⁰

Despite the attention of program planners to the common needs of military and commercial users, three military objectives actually came to dominate the technological agenda of VHSIC participants. First, VHSIC was designed to support the development of advanced integrated circuits for incorporation into specific military systems. Second, the program was to promote the introduction of such circuits into military systems in a "timely and affordable" manner. Third, the program was supposed to ensure that American technology would surpass any technologies potentially available to the Soviets for use in *their* advanced weapons systems. Indeed, technology managers in at least one electronics firm used the firm's participation in VHSIC internally to justify continued high spending on commercial R&D; because of the technological complementarities involved, it was argued that one would be substantially wasted without the other.⁶¹

These objectives influenced both the direction of technological development and the organization of the production infrastructure that ultimately carried it out. The program's technical specifications created a military-oriented technology trajectory that diverged from the needs of most commercial users. This military orientation was then entrenched by the creation of a dedicated production network and by military policies that inhibited the commercial diffusion of VHSIC technology. Nevertheless, in an environment where multiple commercial development trajectories already existed for the

encourages military system suppliers to resort to source control drawings (SCD's), a long list of specifications for manufacture and testing which enable contractors to avoid the hassle and expense of getting commercial or dual-use devices approved for military use. Ironically, this has led to a situation in which a specification system designed to standardize the industry has in fact encouraged the proliferation of costly non-standard chips. The explosion of SCD's impedes quality control efforts as chip producers are overwhelmed with "thousands of separate specifications of devices that are in many cases identical...[The system] produces extremely expensive products that at best are only equal to their commercial, off-the-shelf counterparts and in some cases are worse." see Andrew C. Revkin, "A War Over Military Chips," *Science Digest* (July 1985), pp. 56-79.

⁶⁰In any event, military project managers often waived military-oriented performance requirements, such as man-rated radiation hardness, when such parameters seemed irrelevant to the performance of the chip (interview materials).

⁶¹ interview materials.

underlying technology, this supply-side entrenchment did no particular damage to the technology's prospects for commercialization. Instead, VHSIC's demand-driven military trajectory rendered the program virtually irrelevant to the commercial sector.⁶²

Although it may seem ironic from the perspective of those who favor a dual-use development strategy, the inclusion of private industry representatives in the planning stages of VHSIC actually led program managers to emphasize end-use specifications that diverged from the needs of most commercial users. Drawing on a wealth of technical experience, AGED reviewers understood from the beginning that system considerations would have to guide the design of VHSIC components. VHSIC planners had expected the program to focus on the development of specific devices, emphasizing smaller features and faster speeds. AGED reviewers advised them, however, that it would be highly inefficient to develop high-speed circuits in isolation from the electronic systems that would later have to incorporate them. Consequently, VHSIC planners stipulated that circuit designs would be system driven, that is, designed to meet the specific needs and requirements of military hardware.

Military performance specifications thus defined a unique development trajectory for all program participants. The systems orientation soon encompassed all VHSIC-sponsored work, causing engineers to make technical choices that diverged from the priorities of commercial users. For example, in order to link chip designs to the requirements of particular weapons systems, five of the six Phase I teams developed custom or application-specific chips. Only Texas Instruments, which combined its own systems and semiconductor divisions to form a single VHSIC team, created a standard chip that could be programmed to adapt to various military and civilian applications.⁶³ As for those teams which took the custom design route, military requirements again skewed technological choices away from paths more relevant to commercial needs. For example, VHSIC contractors met the Pentagon's second goal of minimizing turnaround time between technology development and insertion into final systems by choosing design tools which did not maximize utilization of the chip's surface. For profit-seeking

⁶² Theoretically, we would want to explore the issue of opportunity costs--that is, what would have happened had the resources expended on VHSIC been expended, instead, in their best alternative commercial use. In the real world, however, there is no evidence to indicate that a denial of funds to VHSIC would have resulted in comparable government (or private) spending on the development of civilian applications.

⁶³ TI was not among those teams awarded one of three Phase II contracts in October 1984, for reasons that remain unclear, since the Pentagon did not publicly disclose its criteria for selection. The Phase II "winners" were IBM, TRW, and Honeywell. Julian, *High Technology* (1985), p. 53.

commercial firms, however, cost is directly related to circuit-density per chip; the VHSIC program deflected these firms from seeking high density designs that might have paid off over long production runs.⁶⁴

This military-oriented development trajectory was soon entrenched among VHSIC participants by the creation of a VHSIC-specific network of users and producers. Competition was encouraged by forcing VHSIC teams to bid on each of three contract phases; the competition narrowed with each phase. In each case, however, the range of possible bids was already constrained to meet the specific requirements of military systems. Six VHSIC Phase I contractors set up special production lines; of the six, only one, Texas Instruments, primarily served the civilian semiconductor market.⁶⁵

Rather than create a dedicated network of VHSIC contractors, the Pentagon might have chosen to reform its procurement practices. This would have made it easier for private firms to develop VHSIC components that were commercially viable and simultaneously attractive to the Department of Defense (that is, military spin-on instead of commercial spin-off). DOD officials reasoned, however, that a dedicated network would be more responsive to military needs.⁶⁶ Moreover, only by creating a dedicated production network under Pentagon control could VHSIC officials be certain that they were getting components that were better--or at least, different--from components that the Soviets might potentially obtain in international markets.⁶⁷

From the very beginning, similar concerns over national security had precipitated a serious conflict between VHSIC planners and other groups in and around the Pentagon. Worried that VHSIC technology might find its way too easily into the hands of commercial (and, ultimately, military) competitors, the House Armed Services Committee decided (with the support of various Pentagon officials) to place strict export controls on any "technical data" developed in the course of VHSIC research. Under the

⁶⁴ Efficient use of the chip's "real estate" may be less important for custom applications, where the number of custom designs available from a firm may be the crucial competitive variable. But, in that case, VHSIC can have positive commercial effects only if computer-aided design tools developed by the military are characterized by open architectures that can be quickly and flexibly adapted to civilian uses. Quick turnaround technology is certainly important, but even dramatic improvements in military turnaround times (say from seven down to two years) are nowhere near the speeds required by custom chip producers in the commercial marketplace. See Brueckner and Borrus (1984), pp. 47-48.

⁶⁵ Like Texas Instruments, Phase I contractor IBM also served both military and civilian markets, but unlike TI, IBM did not sell semiconductors on the open market. IBM pursues its civilian and military lines of business in strictly separate facilities.

⁶⁶ Interview materials.

⁶⁷ Interview materials.

provisions of the International Traffic in Arms Regulations (ITAR) passed by Congress as part of the Arms Export Control Act of 1976, government permission would be required for the export of any VHSIC technology or technical data subject to potential military application.

In line with the Congressional restrictions, VHSIC's director issued a memorandum to each of the armed forces in December 1980 stating that VHSIC research would be subject to export controls henceforth under both ITAR (which is administered by the State Department) and the Export Administration Regulations (EAR) which are administered by the Department of Commerce. Although these regulations were meant to apply primarily to VHSIC prime contractors and their semiconductor suppliers, university research was also included, given the practical impossibility of distinguishing basic research from process technology with potential military applications. According to a report jointly commissioned by Perry's office, DARPA, and the Office of International Security Affairs at the Department of Energy, such controls might apply even to the mere communication of basic research results to foreign scientists, even within the United States.

Indeed, restrictions were placed on discussion in open (non-classified) technical symposia of either the architectures or performance characteristics of VHSIC contractors' chips; manufacturers were forbidden from discussing details of the software used in either their CAD or fabrication processes. Pentagon restrictions became so stringent, in fact, that VHSIC contractors were forbidden even to publish close-up, front-forward photographs of their products. One story had it that, when the General Accounting Office insisted on such photos for an unclassified report on the program, VHSIC officials were directed to send, instead, an aerial photograph of a parking lot, reduced in size until the cars resembled a cluster of micro-circuitry.⁶⁹

Over time, the fear that export and publication restrictions might spill over onto their commercial operations led some VHSIC contractors to isolate their military work from internally-funded commercial R&D.⁷⁰ Brueckner and Borrus (1984) interviewed

⁶⁸ Betac Corporation, "Final Report: Phase 2 of the United States Technology Transfer Export Controls Project" (Arlington, Va.: Betac, January 1980). Quoted in U.S. Congress, House Committee on Government Operations, *The Classification of Private Ideas*, Report No. 96-1540 (December 22, 1980).

⁶⁹ Julian, *High Technology* (1985), p. 57.

⁷⁰ Another reason that firms began to compartmentalize their military-sponsored R&D was the application of *criminal* penalties to the commercial use of Pentagon money. The criminalization of such activity was Secretary of Defense Weinberger's response to Congressional furor over a number of highly publicized cost

the manager of the commercial LSI division of a large VHSIC prime contractor who "indicated that he keeps 'copious files' detailing the complete abyss between VHSIC and VLSI research" even though the firm's commercial signal processing components were "extremely similar" to VHSIC circuits. The manager indicated that the company was pursuing parallel research efforts in order not to subject *commercial* research and products to DOD publication and export controls.⁷¹

Many VHSIC participants continued to argue, nevertheless, that relevant VHSIC technology would find its way inevitably into commercial semiconductor products: "If we are using improved fabrication techniques in one part of our manufacturing facilities to produce VHSIC devices, and these techniques are sorely needed in our commercial device facility to meet Japanese competition, then the VHSIC technology will 'diffuse' into our commercial operations in spite of Pentagon-imposed barriers."⁷² Worries over restrictions on commercial diffusion may have been misplaced, however, since commercial processing technology has kept pace--indeed has often outpaced--technology developed during the course of the VHSIC project. By 1988, VHSIC had met its phase I goals, establishing facilities which could build chips with geometries 1.25 microns apart. By then, however, commercial chips were already being built with geometries as fine as .7 and .8 microns. Moreover, instead of working to refine existing optical lithography techniques to achieve the smaller device geometries, VHSIC contractors "brute forced" it with expensive E-beam and X-ray lithography. The task of pushing less expensive optical lithography into the submicron range was left to commercial chip producers, who would have followed the same course had VHSIC never existed.⁷³ Asked late in 1986 whether commercial applications would grow out of VHSIC technology, the program's director was unusually candid:

That may happen, but my answer to that question is that if we did our job very, very well, there shouldn't be any commercial applications for these things. That is what we are supposed to be working on--the part that the commercial market wouldn't serve and the military needs. Nobody will build these kinds of chips because there is no way to recover their money in the commercial market, so we

overruns--the Pentagon's \$700 coffee pot--that seemed, for a time, to threaten the Administration's military build-up. Interview materials.

⁷¹Brueckner and Borrus (1984), p. 73.

⁷²quoted in Julian, *High Technology* (1985), p. 57.

⁷³*Electronic Business* (February 6, 1989), p. 56.

have to pay to get them designed. But engineers are bright people, and I am sure they can figure out ways to use almost anything for commercial applications.⁷⁴

Strategic Computing. Viewed with the idea of development trajectories in mind, VHSIC contained from the very beginning many elements that would be expected to inhibit the commercialization of VHSIC technology as well as the capacity of VHSIC participants to benefit from any advances made in their own separate commercial operations. Certain military end-use requirements for VHSIC components diverged significantly from the established needs of large commercial users. The Pentagon created a dedicated network of VHSIC suppliers and outfitted them with specialized production lines. Military policy also truncated the extent to which VHSIC technology could diffuse to commercial users outside of the program. And again, VHSIC occurred in the 1980's, when a set of commercial development trajectories for semiconductor technology had already been well established in the U.S., Western Europe, and Japan.

Similarly, the Strategic Computing Program was constructed from the very beginning to emphasize specific military applications rather than generic research. SCP was designed to demonstrate the utility of the generic technologies it sponsored by having them built into three prototype military systems--an autonomous land vehicle for the Army, a battle management system for the Navy, and a cockpit computer for the Air Force that could "converse" with pilots and offer advice in the heat of combat. Like VHSIC, the Strategic Computing Program's attention to military needs on the demand side created a military-specific development trajectory that was soon entrenched, on the supply side. As the program's emphasis on specific military end-uses shifted the program's main focus from research to development, the bulk of the program's work shifted from university labs to large military contractors. Even in the absence of widespread classification, this shift ended up confining the diffusion of information about technical advances to a narrow circle of military-oriented firms.

Like VHSIC, DARPA's Strategic Computing Program (SCP) was based on the Pentagon's growing realization that military and civilian technology had reversed roles since the 1950's. Technological advances in the commercial sector had far outpaced military efforts to develop several new computer technologies that were each expected to play an essential role in the next-generation of high-tech weaponry. Promoters of the

⁷⁴ E.D. "Sonny" Maynard, Jr., director of VHSIC and electron devices in the Office of the Under Secretary of Defense for Research and Engineering. Quoted by Beth Karlin, *Electronic Business* (August 1, 1986), p. 72.

Strategic Computing Program argued that SCP would spur the development of basic technologies that would ultimately find widespread application in both the military and civilian sectors.

On its surface, the program was designed to develop generic knowledge-based (or "artificial intelligence") software and related data processing approaches. These advances would purportedly allow computers to reason like human experts, to understand human speech, and to recognize objects with machine vision.⁷⁵ Proposed in 1983, SCP was set to last ten years, with a budget approaching \$100 million per year. At the time, however, the move was widely viewed as the U.S. government's primary response to Japan's ambitious Fifth Generation Computer project and, as such, it quickly became mired in partisan bickering over the federal government's appropriate role in the economy. In order to sell the program to Congress and to others within the Reagan Pentagon, DARPA chose purely military goals to drive further development of the technology.

DARPA planned to demonstrate the utility of the generic technologies it sponsored by having them designed at the outset into three prototype military systems--an autonomous land vehicle for the Army, a battle management system for the Navy, and a cockpit computer for the Air Force that could "converse" with pilots and offer advice in the heat of combat. Each of these prototypes had one basic characteristic in common: each was projected to work by processing "knowledge," by "thinking" for itself, instead

⁷⁵ "Expert systems" were themselves spun off from rule-based programming work sponsored by DARPA in the late 1970's. So were Unix-based workstations, which emerged in 1982 from a DARPA-sponsored project at Stanford University and "Berkeley 4.2", developed at the University of California at Berkeley. This apparently successful spin-off again exhibits traits of what we would now want to characterize as spin-on--the original UNIX software was developed for *commercial* purposes; subsequently ARPANET served as a bridge for further co-development by military and commercial users whose needs for developing network communications among different computer systems increasingly converged.

⁷⁶ Japan's Fifth Generation project was designed to develop commercial applications of the same technologies targeted for development by SCP, over approximately the same timeframe. The Japanese were expected to spend approximately \$500 million on the ten-year Fifth Generation Project, plus another \$200 million on a separate five-year Superspeed Computer Project. Japan's government-backed efforts in artificial intelligence and supercomputing are focused explicitly on the enhancement of business and consumer productivity and on the improvement of social services (Datamation, August 1, 1984, p. 42).

⁷⁷ The decision greatly disturbed many computer researchers who appreciated the financial support, but who felt, nevertheless, that SCP's emphasis on showcase projects for each of the armed forces would take too much money and effort away from essential basic research. For more details on the computer science community's initial reaction to SCP, see J. Stowsky, "Beating Our Plowshares into Double-Edged Swords: The Impact of Pentagon Policies on the Commercialization of Advanced Technologies," (BRIE Working Paper #17, April 1986), pp. 54-59.

of merely processing raw numeric data. Each system was thus supposed to drive on-going development in several areas: knowledge-based software, expert systems, machine vision (for the land vehicle), speech recognition (for the cockpit computer), natural language processing (for the cockpit computer), and parallel processing architectures.

Neither the ambitious technical goals, nor the timetable on which they were to be reached, were considered realistic by many in industry and academia.⁷⁹ Commercial proponents of high-speed supercomputers were especially concerned about the program's heavy emphasis on artificial intelligence, a consequence of the program's ambitious prototype goals.⁸⁰ Critics also contended that the achievement of DARPA's goals would depend on "scheduled" technological breakthroughs, even though breakthroughs are by their nature unpredictable. They complained, moreover, that the emphasis on meeting technical milestones for flashy short-term demonstrations would divert money and attention from basic conceptual research.⁸¹

The Strategic Computing Program's attention to military needs on the demand side created a military-specific development trajectory that was soon entrenched, on the supply side. SCP's computer architecture program resembled VHSIC's program for the development of superspeed chips, in that it funded several simultaneous projects in the same area. The system was set up to spur creative competition between research groups and to provide some insurance against the possible failure of individual approaches; it allowed DARPA to play the role of venture capitalist, picking winners and losers from among the best in the field. But SCP had created a set of programmatic goals that effectively isolated the production infrastructure from the pursuit of commercial end-use

⁷⁸ see Willie Schatz and John W. Verity, "Weighing DARPA's AI Plans," *Datamation*, August 1, 1984, pp. 34-43; and Schatz and Verity, "DARPA's Big Push in AI," *Datamation*, February 1984, pp. 48-50.

⁷⁹ Interview materials. See also *Datamation* articles previously cited.

⁸⁰ Interview materials. See also Dwight B. Davis, "Super Computers: A Strategic Imperative?" *High Technology*, May 1984, pp. 44-52; U.S. Congress, Office of Technology Assessment, *Information Technology R&D: Critical Trends and Issues* (Washington, D.C.: U.S. Government Printing Office, February 1985) pp. 57-62; Richard Corrigan, "The Latest Target of the Japanese--U.S. Preeminence in Supercomputers" *National Journal* (April 2, 1983) pp. 688-92; Nancy R. Miller, "Supercomputers" *CRS Review* (March 1984) (Congressional Research Service) pp. 17-19; and "Supercomputing: Number-crunching for research" *Physics Today* (May 1985) pp. 51-53; Others in the computer field were, of course, quite sanguine about the prospects for substantial overlap between advances in knowledge-based software and superspeed computing. "There are some people who are jealous of the large amount of money DARPA is spending on artificial intelligence supercomputing to the exclusion of scientific supercomputing," said Burton J. Smith, vice president in charge of R&D at Denelcor, one of the three U.S. supercomputer manufacturers. But, he added, "I think the artificial intelligence work will prove very beneficial to superspeed computing and vice versa." Quoted in Davis, p. 47.

⁸¹ *Datamation* articles previously cited, plus Andrew Pollack, "Pentagon Sought Smart Truck But It Found Something Else," *New York Times* (May 30, 1989), p. 1.

alternatives. Each competition's pre-set focus was on developing technologies designed to work in particular military systems.

Observers of the Pentagon's growing role in funding basic and applied research into advanced computing worried, also, that commercially-viable spin-offs would be subject to classification and thus restricted to military use. DARPA officials contended that the bulk of SCI's generic research would not be classified, since most of the generic research would be done in universities. Nevertheless, advanced computer architectures were to be developed jointly by universities and private firms, and applied product development would mostly take place in private industry. As the program's emphasis on specific military end-uses shifted the program's main focus from research to development, the bulk of the program's work shifted from university labs to large military contractors.⁸² Even in the absence of widespread classification, this shift ended up confining the diffusion of information about technical advances to a narrow circle of military-oriented firms. Commercially-relevant research results remained trapped within companies that lacked commercial divisions which might be capable of nurturing civilian spin-offs.⁸³

After six years, opinions varied widely about whether there were many civilian spin-offs to be had. The program helped to develop some basic computer technology, though it was by no means clear that the advances depended on sponsorship by SCP. As for applications, the Strategic Computing Program further funded the development of the Connection Machine, a high-speed computer which uses parallel processing and which was finding commercial applications. But the Connection Machine had been under development initially for commercial purposes, anyway; so in this case SCP appears simply to have played the role of venture capitalist. Otherwise, the program focused on purely military applications, and the results of those were mixed. In 1989, DARPA reduced the program's emphasis on knowledge-based software and discontinued the main autonomous vehicle work at Martin Marietta.⁸⁴ Work on a cockpit computer continued and work on a naval battle management system had resulted in a computer that could calculate how best to redeploy ships to compensate for the loss of a part of the fleet.

⁸² Pollack, New York Times (May 30, 1989), p. 1, and interview materials.

⁸³ Michael R. Leibowitz, "Does military R&D stimulate commerce or pork barrel?" Electronic Business (February 6, 1989), pp. 54-58.

⁸⁴ By 1987, the vehicle was supposed to be able to travel across six miles of open desert at speeds up to three miles an hour, avoiding bushes and ditches along the way. In fact, it was only able to travel about 600 yards at about two miles an hour, slower than many people walk (Pollack, New York Times (May 30, 1989), p. 1).

Spin-Off in Historical Perspective: Lessons from the Case Studies

We have looked at four cases of U.S. military involvement in technological development, two from the 1950's and two from the 1980's. One essential similarity differentiates the two technologies developed in the 1950's from those that were being developed in the 1980's--in both of the 1950's cases, when military development of each technology was just beginning, neither had a well-established commercial development trajectory or a widely-recognized commercial production infrastructure. In stark contrast, the Pentagon's 1980's efforts were motivated by the perception that separate, well-established development trajectories in the commercial sector had already yielded technical performance capabilities well beyond those available in the military sector. Military projects sought to upgrade military technology to commercial capabilities and to yoke further commercial advances to the specific needs of military users. Moreover, the 1980's projects proceeded in the context of a perceived threat from foreign producers to continued American dominance of the technologies involved.

The outcomes of the two 1950's cases differ from one another because in one case military involvement created a military-dominated technology development trajectory while in the other it did not. In the case of transistors and integrated circuits, military end-uses promoted a form of the technology that initially converged with the needs of commercial users; this enabled the creation of a commercial development trajectory that evolved alongside the military trajectory, sometimes overlapping, sometimes not. At the same time, military procurement fostered the development of a uniquely independent set of suppliers whose very survival was linked to the constant exploration and expansion of possible (military and non-military) end-uses for the new technology. Military policies also actively promoted the diffusion of basic technological information to potential users and suppliers that were not a part of any military program. Thus, when the end-use requirements of military users began to diverge from the mainstream needs of commercial users, an alternative, self-perpetuating commercial trajectory was already well in place in the industry, due in large part to military policies that had prevented the entrenchment of a military-specific development path.

In contrast, in the case of numerical controls, military end-uses promoted a form of the technology that diverged at the start from the needs of most commercial users. This military-specific development trajectory was then entrenched in the core of the industry as the Air Force set about creating a specialized network of users and suppliers. It was further entrenched by military policies that inhibited diffusion of the technology to

potential users and suppliers who were not a part of the military network. While the large American machine tool makers focused on meeting the needs of large-scale, technologically advanced military contractors, their competitors in Japan were developing close links to large industrial firms and their networks of small and medium-sized subcontractors. When the development of the microprocessor and simpler programming languages made the technology of numerical control widely accessible for everyday machining operations, the Japanese industry was better configured than the American industry to mass produce low-cost NC tools.

The outcomes of the 1980's cases differ from the outcomes of the 1950's cases because both projects sought to develop the latest generation of a technology that was already under development (both here and abroad) in the commercial sector. Because of that, both programs naturally focused on military-specific forms of the technology that had no commercial markets and were therefore not being developed by commercial firms. In both cases, military-specific objectives came to dominate the objective of dual-use. In the case of VHSIC, the priority of immediate systems applications shifted the program's focus from the semiconductor merchants to the military systems houses; a similar shift from university labs to military systems houses occurred during the Strategic Computing Project, as generic technologies were tailored to the needs of specific military products. In the end, both projects were moderately successful at developing the applications that were desired by the military services and basically unsuccessful at creating dual-use technologies or commercial spin-offs.

Conclusion: From Spin-Off to Spin-On

The issue is not whether spin-off will continue to occur, or indeed, whether spin-on and spin-off can co-exist; of course it will and of course they can. In terms of long-term competitiveness, the critical issue has to do with which process is faster. Which provides the quicker route toward full exploitation of the technological complementarities between military and commercial applications?

The United States can no longer afford to divide its technology base into two separate entities, one for the battlefield, one for the marketplace. Despite their demonstrated capacity for saving American lives, most of the high-tech weapons used to such stunning effect in the Persian Gulf War were based on technologies more than ten years out of date. In the ensuing decade, technological leadership has passed to others.

When allied commanders urgently needed spare battery packs to power their command and control computers in the midst of battle, they had to send to Paris and Tokyo to get them.

For the foreseeable future America's military technology base will be shaped by three trends: declining military budgets, an expanding overlap between military and commercial technologies, and an increasingly global marketplace for high technology in which the much larger and more dynamic commercial component determines the direction of innovation. There will be more spin-ons from commercial producers to the military sector and fewer spin-offs in the opposite direction.

The continued bifurcation of the U.S. technology base creates serious security risks that only intensify as high volume consumer products become more sophisticated technologically. The latest generation of consumer products--camcorders, electronic still cameras, compact disc players, and hand-held TV's--plus new high volume products developed for office and home use--portable faxes, copiers and printers, electronic datebooks, laptop computers, optical disk storage systems, smartcards, and portable telephones--have much in common technologically with engineering workstations, telecommunications networks, military avionics, and other gadgetry of obvious and increasing value to the U.S. Department of Defense.

Most important, the development of these products for mass consumer markets creates a huge demand for low cost, high quality production of components and subsystems, most of which are critical for both military and industrial uses. These include everything from semiconductors and storage devices to packaging, optics, and interfaces. For instance, the new high volume products contain a wealth of silicon chip technology, ranging from memory and microprocessors to charge-coupled devices. In addition, commercial firms already produce enormous quantities of sophisticated optoelectronic components, including laser diodes and detectors, and LCD shutters, scanners, and filters, for use in mass market applications such as compact disks. Japanese miniature TV's are the leading edge users of flat-panel, amorphous silicon-thin film, liquid crystal display technology and other interface technologies that are soon to be widely applied in both industrial and military systems.

Consumer applications also drive the development of militarily-significant storage and packaging technologies. Advanced digital auto tape is as dense a storage

medium as high performance computer disk technology; optical storage is beginning to spread into industrial and military data applications after first being refined for consumer use in compact and laser disks. High volume manufacturing requirements have driven the development of innovative packaging technologies that range from tape automated bonding and chip-on-board to multi-chip modules; producers of hand-held LCD TV's already use packaging technology as sophisticated as that being used in the most advanced American military systems.

Finally, new consumer products are sparking innovations in precision electromechanical and feromechanical components like motors, gears, and switch assemblies, as well as recording heads, transformers, and magnets. Other significant examples of sophisticated inputs that are commonly found throughout the consumer electronics industries range from the high quality lenses used in electronic still cameras and camcorders to the low-end print engines that drive desk-top copiers and laser printers.

Economies of scale in the manufacture of such products make it needlessly (and perhaps unaffordably) expensive for military contractors to produce independently of the commercial industrial base. Participation in global high volume markets now gives private firms the capacity to amortize the development and manufacturing costs of technological inputs that were once thought too expensive and risky for any entity other than the Pentagon to support. Massive demand for new products creates similar advantages for suppliers of components and other technology inputs, too, both because they can drive down per-unit costs through scale economies in production and because they can spread the costs of research and development across a much higher volume of sales. Most important, however, is the notion that a spin-on strategy can diffuse technological advances more quickly than a spin-off strategy. By overcoming military isolation from the dynamics of commercial technology development, a spin-on strategy improves the ability of both sectors to generate and share essential technological learning.

Today's most advanced commercial suppliers of high-volume, high-tech products do their market research by introducing products and then fine-tuning product configurations and volumes to actual demand. They utilize an extremely short and efficient development cycle in order to master flexible, low-inventory manufacturing with high quality at low cost. This sort of learning-by-doing can enable firms to master

several different kinds of highly market-responsive product development, materials, and manufacturing skills. The learning eventually accumulates to a kind of localized knowledge base (that is, internal to the firm). It is a kind of knowledge that is not easily spread through either markets (in the form of reverse-engineering or learning-by-using) or scientific conferences. Due to its evolutionary and partly tacit nature, much of this knowledge simply accumulates in the firms or network of firms where it originates.

The argument for pursuing a spin-on strategy is, at its root, an argument in favor of maximizing the available opportunities for generating and diffusing technological *learning* throughout the American economy. When military contractors remain isolated from the product performance and low-cost manufacturing demands of high volume consumer markets, or when the Pentagon attempts to harness the cutting-edge expertise of commercial firms only to yoke their development efforts to the creation of low-volume, military-specific product applications, the Department of Defense sacrifices the opportunity to benefit from the important technological spillovers that now run from commercial to military products. Military product markets are typically too small, and the pace of product introduction too slow, to generate the same breadth of cost-reducing, knowledge-enhancing manufacturing experience that accrues, in the same amount of time, in the commercial sector. DOD's task, in this view, is to gain access to the commercial knowledge base without compromising it, either by linking its evolution at the outset to military-specific ends or by constraining its expansion with security restrictions after the fact.

Declining military budgets, an increasingly unified technology base for both military and commercial products, and the globalization of markets for those base technologies--these trends mean that the cost of maintaining two technology bases is increasingly untenable. The alternative is to integrate them. The best way for the United States to bolster its military technology base is to encourage military contractors to test themselves in the commercial marketplace.

The Department of Defense must reform procurement rules which have built a wall between military and commercial practices. Wherever possible, DOD must reduce obstacles to the use of commercially-developed technologies in military systems. At the very least, DOD should limit the impact of its rules to prime contractors, leaving them free to follow commercial practices with their own customers. This will accelerate the trend toward viewing prime contractors as specialists in design and systems integration,

subcontracting for everything except final assembly. The Pentagon would still require prime contractors to develop methods for assuring quality control among commercial suppliers, but without mandating any particular method.

At the same time, DOD must delay the point at which military-specific characteristics are built into the products it buys. Today's military applications are differentiated from their commercial counterparts beginning deep at the sub-component level. Product differentiation should migrate to a higher level in the system, to software and systems integration, where American firms still enjoy a modicum of technological leadership. Functional requirements should replace design specifications. Burdensome qualification requirements should be eliminated for producers of materials, subcomponents, and parts.

For sub-systems that still must adhere to military-specific performance requirements, attempts should be made by military contractors to create the sorts of scale economies that are typical of commercial production. DOD should help its contractors to develop generic sub-system descriptions, so that sub-systems can be consolidated into a limited number of modules. The modules can then be manufactured in large volume, since they are designed to fit a wide variety of final systems.

Finally, DOD must allow its contractors to develop their own quality-control methodologies. Contractors currently suffer at the hands of Pentagon bureaucrats who think that the way to ensure quality is to specify production procedures and to conduct specialized product tests. Commercial producers know better. They have replaced post-production testing with quality-control systems that spot quality defects while manufacturing is still in process, not after it is finished. Quality is built in, not tested in.

There is much that the U.S. Department of Defense can still do to reverse the deteriorating health of the military technology base. Besides integrating production that is now separated into military and commercial lines and removing export-control barriers which inhibit commercially-oriented facilities from accepting military contracts, DOD can develop explicit policies to promote the commercial development of core components that have both military and commercial applications. This may include DOD support for industry research consortia and the redirection of national R&D assets, such as the national labs.

In any case, military-sponsored R&D should be designed around prototypes that can be used in both commercial and military applications. Contractors selected to perform such research should have to demonstrate their capacity for transforming their prototypes into commercially-successful products. An example of one such contractor is Boeing, which along with Lockheed and General Dynamics, won the Air Force contract to build the advanced tactical fighter. The award was surprising to many, because two members of the team had not built a tactical fighter in decades. But Boeing, and to a lesser extent Lockheed, brought to the process a wealth of technology developed through competition in commercial as well as military markets across the globe.

Since the late 1980's, America's debate about industrial "competitiveness" has often turned into a debate over the Pentagon's de facto industrial policy, at least to the extent that public discussion has been able to transcend mythological distinctions between government intervention and the "free" market. Arguments have raged about whether Pentagon resources are (or should be) directed to customers that are straightforwardly military or, more stealthily, to customers who are essentially commercial. This is a distinction, we have argued, that is increasingly without a difference. The technology base from which American firms compete in today's commercial markets is the same technology base that determines whether or not the United States is prepared to respond to the national security concerns of the future. Americans can conjure many potential threats to their well-being, but only one technological arsenal with which to meet them.