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Military Needs, Commercial Realities, and the Development of the Transistor, 1948-1958

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Of the many technological projects that the military has supported since World War II, none have proved more important than the transistor. In this essay, Thomas Misa examines the means the Army Signal Corps used to advance the new field of solid-state electronics. In treating the development phase of the transistor, Misa emphasizes technology as expanding knowledge and places the subject in an institutional context. The essay well illustrates the complexities of initiating high technology enterprises, particularly the problems that can arise when innovations begin to move from military applications to commercial use.

It was in the context of the search for an effective replacement for mechanical telephone relays that scientists at Bell Telephone Laboratories invented the transistor.[1] The device unveiled in 1948 was fragile, cumbersome, and clearly ill-suited for service outside the laboratory; yet within a decade the transistor had become the core of a rapidly growing sector of the electronics industry with annual sales exceeding $100 million. This essay will argue that the transition between invention and mass marketing, the development phase,[2] was to a large extent guided and funded by the United States military and in particular by the Army Signal Corps. This active role was not without its drawbacks for the emerging industry, however, as we shall show by examining the conflict between the needs of the military and of civilian industries, including those of the Bell System itself.

More generally this essay maintains that institutions such as military agencies can act as entrepreneurs and hence shape the process of technological change. Historians typically conceive

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1. One exception to the general neglect of the history of modern electronics is the invention of the transistor. See Charles Weiner, "How the Transistor Emerged," *IEEE Spectrum* (January 1973): 24–33; Lillian H. Hoddeson, "The Discovery of the Point-contact Transistor," *Historical Studies in the Physical Sciences* 12 (1981): 41–76. An important study is Ernest Braun and Stuart MacDonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics* (London: Cambridge University Press, 1978); see also idem, "The Transistor and Attitude to Change," *American Journal of Physics* 45 (November 1977): 1061–65. Of several accounts of the transistor written by Bell Laboratories personnel, one merits mention here: William Shockley, "The Path to the Conception of the Junction Transistor," *IEEE Transactions on Electron Devices* ED-23 (July 1976): 587–620. See also the special issue of the trade journal *Electronics* 53 (17 April 1980); M. Gibbons and C. Johnson, "Science, Technology and the Development of the Transistor," in B. Barnes and D. Edge, eds., *Science in Context* (Cambridge, MA.: The MIT Press, 1982), pp. 177–85; S. Millman, ed., *A History of Engineering and Science in the Bell System: Physical Sciences (1925–1980)* (Murray Hill, NJ: Bell Laboratories, 1983), 4: 71–107; Hoddeson, "The Roots of Solid-state Research at Bell Labs," *Physics Today* 30 (March 1977): 23–30; and idem, "The Entry of the Quantum Theory of Solids into the Bell Telephone Laboratories, 1925–40: A Case-Study of the Industrial Application of Fundamental Science," *Minerva* 18 (1980): 422–47. On the integrated circuit, see Michael F. Wolff, "The Genesis of the Integrated Circuit," *IEEE Spectrum* (August 1976): 45–53; and Jack S. Kelly, "Invention of the Integrated Circuit," *IEEE Transactions on Electron Devices* ED-23 (July 1976): 648–54.

2. Several economists have studied the transistor but have failed to appreciate the wide gulf separating invention from marketing. For example, one study stresses the scientific basis for the invention of the transistor: Richard R. Nelson, "The Link Between Science and Invention: The Case of the Transistor," in National Bureau of Economic Research,

of entrepreneurs as individuals responsible for inventing a technology, presiding over its development, and contributing to its eventual shape and style.[3] In the case of the transistor, the Army Signal Corps had a marked effect on the content and even the style of the technology. By sponsoring applications studies, conferences, and publications in the late 1940s and early 1950s, the military services ensured a rapid dissemination of the new technology to the electronics industry. By subsidizing the construction of manufacturing facilities and overseeing the setting of standards, they influenced the size and structure of the emerging transistor industry. And finally, military requirements biased the industry toward the development of specific types of transistors. Military sponsorship helped shield the new technology from undue criticism and economic constraint and also provided the necessary momentum to push it through the development stage to commercialization.

The Search for the Transistor

The development of the transistor occurred in a period of rapid growth and qualitative change in the American electronics industry. Whereas in 1930 radios had accounted for 90 percent of the industry's total sales of $103.5 million, after World War II radio's share of sales dropped to 20 percent, owing to the rapid acceptance of television and the expanding needs of industry and the military. In 1950 total civilian sales of electronics equipment reached $1.1 billion, and by the end of the decade civilian plus military sales topped $10 billion. Wallace B. Blood, business manager of the trade journal *Electronics,* pro-

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The Rate and Direction of Inventive Activity: Economic and Social Factors (Princeton: Princeton University Press, 1962), pp. 549–83. Another study stresses the role of market forces in the dissemination of semiconductor technology: John E. Tilton, *International Diffusion of Technology: The Case of Semiconductors* (Washington, D.C.: Brookings Institution, 1971). There are problems with both of these approaches. During development many organizational factors external to science are critical. Further, in the United States a great deal of transistor technology was disseminated before any vigorous market existed.

In order to explore the important but often neglected phase between invention and mass marketing, I will focus explicitly on the development phase of the transistor. For concepts I have drawn on John M. Staudenmaier, "Design and Ambience: Historians and Technology, 1958–77," (Ph.D. dissertation, University of Pennsylvania, 1980), pp. 138–48; and Thomas P. Hughes, "The Development Phase of Technological Change," *Technology and Culture* 17 (July 1976): 423–31.

3. For a classic discussion of entrepreneurs, see Thomas P. Hughes, "The Electrification of America: The Systems Builders," *Technology and Culture* 20 (1979): 124–61.

claimed that electronics manufacturing had undergone "a metamorphosis unique in industrial history."[4] Yet, despite this striking sales spurt, the really fundamental change in the industry was technical—the introduction of solid-state electronics, a radically new technology that broke the vacuum tube's half-century monopoly.

As the vanguard of this revolution, the Bell Telephone Laboratories were well prepared to translate innovative technical concepts into industrial realities. Scientific curiosity, technological utility, and corporate goals had successfully mixed in the Bell System before, most notably around World War I in the exploitation of Lee De Forest's original patent for the vacuum tube.[5] With the transistor, a complex of institutional and cognitive factors were once again to influence technological development.

The impetus to develop a solid-state amplifying device came from Bell's director of research, Mervin J. Kelly. Kelly had long desired to replace the mechanical relays in telephone exchanges with electronic relays. In 1939 he had placed two physicists, experimentalist Walter Brattain and solid-state theoretician William Shockley, on a project to construct a solid-state amplifier with the semiconductor copper oxide. The device failed to behave as predicted, however, and the plans were set aside to make room for war-related work. Between mid-1941 and 1945 Bell turned over nearly three-quarters of its facilities to such military projects as radar, radio and wire-based communications, aircraft training simulators, antisubmarine warfare, proximity fuzes, electronic computers for gunfire control, electronic countermeasures systems, and research on materials for the atomic bomb. Brattain and Shockley left the Laboratories for separate assignments, but Bell continued solid-state research by sponsoring a team of chemists and metallurgists who worked under the direction of MIT's Radiation Laboratory to purify the semiconductor material silicon for use in radar. Meanwhile a group at Purdue University

4. *Electronics* 53, p. 276.

5. For contrasting interpretations of the development of the vacuum tube, see Leonard S. Reich, "Industrial Research and the Pursuit of Corporate Security: The Early Years of Bell Labs," *Business History Review* 54 (Winter 1980): 504–29; and Lillian Hoddeson, "The Emergence of Basic Research in the Bell Telephone System, 1875–1915," *Technology and Culture* 22 (July 1981): 512–44. See also Arturo Russo, "Fundamental Research at Bell Laboratories: The Discovery of Electron Diffraction," *Historical Studies in the Physical Sciences* 12 (1981): 117–60.

headed by physicist Karl Lark-Horovitz also conducted research on yet another semiconductor material, germanium. The experiments of the Purdue group were so similar to those done later at Bell that some writers have speculated that had Lark-Horovitz been looking for a solid-state amplifier, instead of exploring general physical phenomena, his group would have invented the transistor.[6]

One important outcome of the war was that new and mutually satisfying relationships were forged between the communities of science, technology, and government. Vannevar Bush, an MIT electrical engineer; James B. Conant, a chemist and the president of Harvard University; and other members of the country's scientific and engineering elite had created new federally funded but civilian run organizations that had proved capable of enlisting and directing the nation's technological expertise.[7] Yet immediately after the end of hostilities, researchers found themselves without a federal patron. Designed as a purely wartime institution, Bush's Office of Scientific Research and Development (OSRD) was disbanded in 1945, and it was not until 1950, with the act authorizing the National Science Foundation, that Congress created a nonmilitary mechanism to fund basic research. In the interim, several military agencies stepped into the breech. A Joint Research and Development Board was organized in 1946 to coordinate military research and development, but it remained weak, and the Office of Naval Research soon emerged as the largest patron of the post-

6. My discussion of the invention of the transistor follows Braun and MacDonald, *Revolution in Miniature,* chapters 1–4 and Hoddeson, "Discovery." For Kelly's motivation for doing semiconductor research, see Hoddeson, "Discovery," pp. 45, 47, 52–54. Kelly joined the research division of the engineering department of Western Electric, the predecessor of the Bell Telephone Laboratories, in 1918; preceding his appointment as director of research in 1936, he was director of vacuum tube development and director of transmission instruments and electronics. He became executive vice president of the Laboratories in 1944 and president in 1951. See *Bell Telephone Magazine* 32 (Summer 1953): 70–71; and Michael F. Wolff, "Mervin J. Kelly: Manager and Motivator," *IEEE Spectrum* 20 (December 1983): 71–75. For Kelly's views on research and development, see his essay, "The Bell Telephone Laboratories—An Example of an Institute of Creative Technology," *Proceedings of the Royal Society* 203A (1950): 287–301. For a technical account of Bell's wartime projects, see M.D. Fagan, ed., *A History of Engineering and Science in the Bell System: National Service in War and Peace (1925–1975)* (Murray Hill, NJ: Bell Laboratories, 1978), 2: 3–351.

7. For background concerning science and technology in World War II, see Daniel J. Kevles, *The Physicists* (New York: Knopf, 1977), pp. 287–348; Carroll Pursell, "Science Agencies in World War II: The OSRD and Its Challengers," in N. Reingold, ed., *The Sciences in the American Context* (Washington, D.C.: Smithsonian Press, 1979), pp. 359–78; and James Phinney Baxter, *Scientists Against Time* (Cambridge, MA: The MIT Press, 1968).

war period.[8] While this more complicated system of support was being set up, university efforts, including the transistor group at Purdue,[9] were left in limbo. In contrast, private industrial efforts benefited from the relative stability of their own (mostly internal) funding.

Bell was thus not only well prepared but also well situated in the postwar period to make the most of the accumulated experience with semiconducting materials. With stable research funding, a multidisciplinary staff of over 2000 scientists and engineers, and a ready market in the massive Bell System, the Laboratories had the resources and the incentive to mount a major technological effort in the new field of semiconductor electronics.[10] The final element contributing to its program was a goal-oriented approach: the Laboratories would not repeat the near miss of Lark-Horovitz at Purdue. Having been promoted to vice-president in charge of research, Kelly signed the authorization to begin solid-state work in June 1945, two months before V-J Day. Shockley and physical chemist Stanley Morgan headed a new solid-state physics department that included Brattain; John Bardeen, a theoretician from the Naval Ordnance Laboratory; experimentalist Gerald Pearson; physi-

8. On the postwar science policy debate, see Kevles, "The National Science Foundation and the Debate over Postwar Research Policy, 1942–1945: A Political Interpretation of *Science—The Endless Frontier*," *Isis* 68 (1977): 5–26; and idem, "Scientists, the Military, and the Control of Postwar Defense Research: The Case of the Research Board for National Security, 1944–46," *Technology and Culture* 16 (January 1975): 20–47. On the ONR see Harvey M. Sapolsky, "Academic Science and the Military: The Years Since the Second World War," in Reingold, *American Context*, pp. 379–99; and Mina Rees, "The Computing Program of the Office of Naval Research," *Annals of the History of Computing* 4 (1982): 102–20.

9. To at least one person, the Purdue and Bell efforts were competing. When Bell announced the transistor in June 1948, William Shockley, one of the Laboratories' three physicists who were to share in the 1956 Nobel Prize in physics for the transistor, reportedly cornered a Signal Corps officer to ask, "Tell me one thing, have Lark Horowitz and his people at Purdue already discovered this effect, and perchance has the military put a TOP SECRET wrap on it?" See *Microwave Journal* 8 (July 1966): 96. No all-encompassing security restriction was placed on the transistor, although this option was discussed during 1948.

10. Incorporated in 1925, Bell Telephone Laboratories was owned jointly by American Telephone and Telegraph (AT&T) and Western Electric. AT&T authorized and paid for basic research; Western Electric authorized and paid for the development of technology applicable to its products. In early 1952 the total Laboratories' staff numbered 6900, of whom 2500 were engineers and scientists; 2100 were draftsmen, technical assistants, and mechanics; and the remaining 2300 were nontechnical personnel and managers. For military work, Western Electric was usually the prime contractor, while the Laboratories carried out projects as a subcontractor. See Robert N. Anthony, *Management Controls in Industrial Research Organizations* (Boston: Harvard University Press, 1952), pp. 382–84. Throughout this essay, unless explicitly noted, the terms "Bell" and "the Laboratories" refer to Bell Telephone Laboratories.

cal chemist Robert Gibney; and Hilbert Moore, an electronics specialist. By Christmas 1947 the group had built their first device. With an ungainly laboratory apparatus, Bardeen and Brattain demonstrated convincingly that electrical amplification could occur between two closely spaced contacts on the surface of a sample of germanium (figure 1). Now began the complex and difficult process of developing a laboratory curiosity into an electronic device capable of functioning in the real world.

Several changes in Bell's organization expedited the development effort. At the time the Laboratories' physicists, chemists, and mathematicians tended to associate only with colleagues in their own discipline. As Bell's vice-president Ralph Bown observed, "Such a grouping plan tends to create dividing walls of thought, and alongside such walls often are moats in which good ideas may sink out of sight."[11] To prevent its newly invented device from slipping into such a moat, Bell formed a special project group early in 1948. A three-man committee coordinated the effort: physicist Shockley headed transistor research, physical chemist Addison H. White led research on electronic materials, and electrical engineer Jack A. Morton directed fundamental development. In this position and later as head of the entire transistor development effort, Morton had critical perspective on the difficulties Bell would encounter with developing transistors for both civilian and military use. His project reports provide the basis for a middle level of analysis between detailed technical reports and publicity-oriented articles.

Morton's group played a key role. Its specific tasks included examining the factors controlling the device's amplification bandwidth and noise level, improving the energy gain per stage of amplification, and conducting studies of the basic materials, manufacturing processes, and precise structures needed in order to produce transistors for specific applications. Organizationally separate from the physicists, chemists, and metallurgists, this group had the general responsibility for coordinating the work of these specialists. This division of labor preserved a degree of autonomy for the scientists while ensuring that Bell's broad spectrum of resources would be fully utilized in the process of development. Capitalizing on its postwar organization

11. Ralph Bown, "The Transistor as an Industrial Research Episode," *Scientific Monthly* 80 (January 1955): 45.

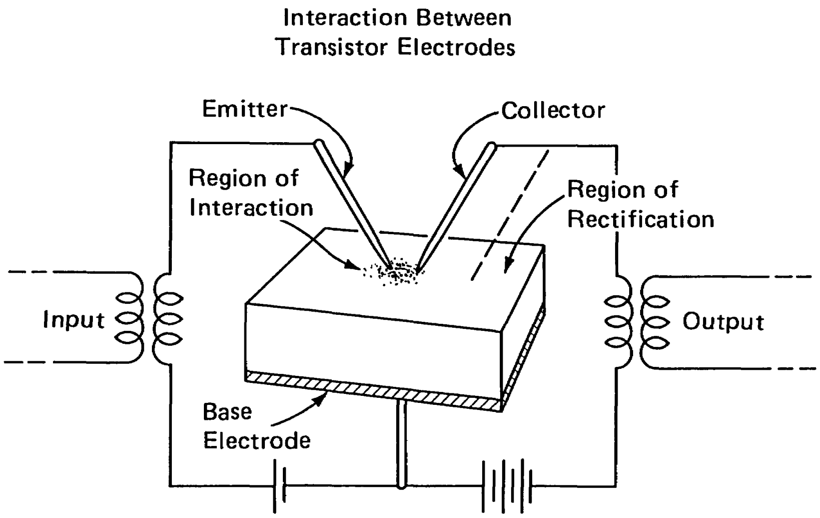

Figure 1
Point contact transistor as amplifier. Through electronic phenomena not well understood when the transistor was invented, changes in the voltage across the input leads produced changes in the voltage across the output leads. A microphone, for example, could be connected to the input and a loudspeaker to the output. *Source: Bell Laboratories Record* 50 (December 1972): 352.

and its early jump on competitors, Bell dominated transistor technology into the mid-1950s. As late as 1955 the Laboratories still collected 37 percent of the patents issued in the semiconductor field (table 1).[12]

Although the initial model device seemed to hold great promise, it also posed a formidable array of technical problems. The first was its name. During the spring of 1948 the staff debated a variety of imaginative names, including semiconductor triode, surface states triode, crystal triode, and iotatron, before "transistor" became widely accepted.[13] A more significant problem was that the early devices were a curious blend of abstract quantum mechanics and cut-and-try tinkering. Solid-state physicists could explain reasonably well the phe-

12. Tilton, *International Diffusion,* p. 57; and Francis Bello, "The Year of the Transistor," *Fortune* (March 1953): 132. For general relationships between organization and technological efforts, see Bruce Parrott, "The Organizational Environment of Soviet Applied Science," in L. L. Lubrano and S. G. Solomon, eds., *The Social Context of Soviet Science* (Boulder: Westview Press, 1980), pp. 69–100, esp. 70–71; and essays by Douglas and Allison in this volume.

13. L. A. Meacham, et al., "Terminology for Semiconductor Triodes—Committee Recommendations–Case 38139-8," Memorandum for File, MM-48-130-10, 28 May 1948, located in binder: Publications, Jack A. Morton Collection, Bell Laboratories Archive, Short Hills, New Jersey (collection hereafter cited as JAM Collection).

Table 1
Breakdown of semiconductor patents by firms (percent)

	1952	1953	1954	1955	1956
Bell Laboratories	56	51	46	37	26
Tube Firms [a]	37	40	38	42	54
New Firms [b]	7	9	16	21	20
Total Number of Patents Granted	60	92	79	73	186

a. Includes Radio Corporation of America, General Electric, Westinghouse, Sylvania, Philco-Ford, and Raytheon, all firms with previous experience manufacturing vacuum tubes.
b. Includes International Business Machines, Motorola, Hughes, International Telephone and Telegraph, and Clevite, firms that had been set up explicitly to manufacture semiconductor components or that had no previous experience manufacturing vacuum tubes.
Source: John Tilton, *International Diffusion of Technology* (Washington, D.C.: Brookings Institution, 1971), p. 57.

nomena that occurred *within* materials, but the point-contact transistor exploited poorly understood *surface* phenomena. Accordingly, the group relied more on empirical practice than physical theories to guide their work. For example, an enigmatic step called "forming" was used to attach the two closely spaced metal wires to the purified semiconductor pellet. Passing a burst of current through the germanium-metal contact attached the wires to the transistor and also, for reasons that were unclear, improved its overall performance. Finally, reliability was a problem. After manufacture, which consisted of hand assembly under a microscope, the devices were tested to determine if they would amplify electronic signals. Most did not. Four-fifths of the earliest devices were rejected, and even those that passed had serious weaknesses. Early transistors had operating characteristics that varied with the ambient temperature; they suffered from extremely high electrical noise; and they had painfully modest maximum power ratings and limited frequency ranges.[14]

Despite the transistor's many obvious shortcomings, its potential advantages were widely discussed in the trade literature.

14. B. N. Slade, "Survey of Transistor Development (Part 1), "*Radio and Television News* 48 (September 1952): 43; idem, "Survey of Transistor Development (Part 2)," *Radio and Television News* 48 (October 1952): 65, 112–14; Millman, *History of Engineering and Science*, pp. 119–22; Mervin J. Kelly, "The First Five Years of the Transistor," *Bell Telephone Magazine* 32 (Summer 1953): 77; and Hugo Gernsback, "Transistor Trends: Transistor Evolution has only Begun," *Radio-Electronics* 29 (May 1958): 33.

Even a miniature vacuum tube was much larger than the tiny transistor. Further, tubes required a bulky auxiliary power supply to heat the electrodes, which tended to burn out after a few thousand hours of use.[15] Pictures of the rooms filled with hot, glowing tubes needed for the first electronic computers offer striking testimony of the acute need for smaller substitutes. Bell Telephone Laboratories clearly saw the transistor's promise and committed resources toward its realization, but at the same time the transistor benefited from a timely fit into a preexisting program to miniaturize electronic military equipment.

The Military Promotes the New Technology

A conscious program to miniaturize military electronics began in the late 1930s when the Army Signal Corps Engineering Laboratory (SCEL) at Fort Monmouth, New Jersey, designed the first "walkie-talkie." A football-size, two-tube transmitter-receiver with a separate telephone handpiece, the walkie-talkie was meant for infantrymen on reconnaissance missions and for forward-observer fire-control personnel. The device allowed individual soldiers to remain in contact with commanders without having to drag a telephone wire or carry a heavy, full-size radio. In the immediate prewar period, the Signal Corps Engineering Laboratory developed a six-pound, completely integrated "handie-talkie," which served during the war as the workhorse of battlefield communications.

The SCEL made further refinements to Army communications during the war, but they also encountered several technical and organizational difficulties. As the number of items of electronic equipment increased and as evolving military tactics required ever more complex gear, the Signal Corps' procurement system proved incapable of coordinating the process. Moreover, reports received by the SCEL during and immediately after the war revealed many inadequacies in Army electronics. One major problem was an inability to stand up to environmental extremes such as fungus, moisture, and corro-

15. For a systematic comparison of the transistor and the vacuum tube circa 1953, see Emerick Toth and William N. Keller, "Principles of Transistor Application and System Design," in *Symposium on the Application of Transistors to Military Electronics Equipment,* held at Yale University, 2–3 September 1953, sponsored by the Committee on Electronics (Research and Development), Office of the Secretary of Defense. Copy in Library of Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia, Pennsylvania.

sion in the jungle and freezing in the arctic. Other problems could be traced to the battlefield rigors of shock, vibration, temperature changes, and weather. And the sheer size and bulk of the equipment hampered operations. In response to these problems and because many Signal Corps personnel anticipated that electronics would assume even greater importance in postwar communications, surveillance, fire control, countermeasures, and intelligence, the Corps undertook a long-range research and development program to produce an integrated system of communications equipment. Miniaturization received particular emphasis.[16]

From the start the SCEL focused its miniaturization efforts on circuit-assembly techniques. One avenue it explored was the ceramic-based circuit developed for the National Bureau of Standards by the Centralab Division of the Globe-Union Corporation. Although this technique was successful in the miniature circuits of the Army's proximity fuze, it required a large investment in specialized production equipment and could be used only for simple, resistor-capacitor circuits. Complex circuits remained a problem. The labor-intensive process of hand soldering components was the only well-tested mass production method, but there were limits to reducing the size of circuits because the wiring became chaotic and prone to fail.

Working with industry, the SCEL invented, patented, and refined an automatic soldering system that bypassed the wiring problem. Individual components were plugged into a plastic board on whose backside a wiring diagram had been etched in copper. When the copper side was dipped into a molten solder bath, the components were automatically attached to the board and also properly connected. To underscore the potential of the process for mass production, the Signal Corps named it "Auto-Sembly." Perfecting this new production method oc-

16. In 1946 the SCEL Ad Hoc Committee on Miniaturization stated that "miniaturization should and will be a major objective in the design of future Signal Corps' equipment." William R. Stevenson, "Miniaturization and Microminiaturization of Army Communications—Electronics, 1946–1964," U.S. Army Electronics Command, Fort Monmouth, New Jersey, Historical Monograph 1 (Unpublished manuscript, 1966), pp. 1–12, quote p. 12 (volume hereafter cited as Army Miniaturization Monograph). For the Signal Corps in World War II, see its three-part official history: Dulany Terrett, *The Signal Corps: The Emergency* (Washington, D.C.: Government Printing Office, 1956); George Raynor Thompson, et al., *The Signal Corps: The Test* (Washington, D.C.: Government Printing Office, 1957); and George Raynor Thompson and Dixie R. Harris, *The Signal Corps: The Outcome* (Washington, D.C.: Government Printing Office, 1966)

cupied the SCEL into the early 1960s.[17] Auto-Sembly was an important step forward in miniaturization that would become even more useful when paired with the tiny solid-state components emerging from Bell Telephone Laboratories.

By the spring of 1948 Bell was satisfied that their preliminary work on transistors would be patentable, and a public demonstration was set for June 30. A week before the unveiling, Oliver E. Buckley, the president of the Laboratories, invited the military services for an advance look. Buckley conducted this special briefing, and Ralph Bown demonstrated the ability of the transistor to serve variously as a telephone amplifier, a radio receiver, and a circuit oscillator. There were six people in the group, two each from the Army, Navy, and Air Force. The two Army representatives—Colonel E.R. Petzing, commanding officer of the SCEL, and Harold A. Zahl, the new director of research of the SCEL—talked later that afternoon with Bell executives Bown, James McRae, and Donald Quarles about a possible Signal Corps contract in the transistor field. Quarles, who later became Assistant Secretary of Defense for Research and Development, is reported to have replied bluntly that Bell's research was not for sale. Nevertheless, arrangements were made to keep the services informed about new applications. On July 2 Zahl submitted an enthusiastic report about the meeting to his commanding officer: "The phenomena . . . will have great significance in the Signal Corps research and development program. Of particular interest is apparent promise of reduction in power requirements for electronic gear, miniaturization aspects, new current techniques, etc."[18]

Describing his "immediate course of action," Zahl planned to inform all SCEL personnel of the new device, to arrange visits to Bell for key staff, and to procure sample transistors from Bell. Within the month the SCEL formed a transistor group composed of two engineers and one physicist, in its thermionics branch, which, like Bell's, was part of the vacuum tube department. Although the transistor effort grew in a few years to full branch status, with approximately forty engineers, physicists, and chemists, the limited availability of transistors hampered early work. In an attempt to increase the number of available

17. Army Miniaturization Monograph, pp. 18–114.

18. For a reprint of Zahl's 1948 report and his later recollections of the meeting with Bell, see *Microwave Journal* 8 (July 1966): 94, 96.

devices, the SCEL created a small manufacturing facility, which produced fifty point-contact transistors in 1949.[19]

Following Zahl's enthusiastic report and the Signal Corps' initial tests, the military services persuaded Bell to sign a contract for study of applications. As parties to the June 1949 contract, all three services charged the Laboratories with investigating the usefulness of the device in switching circuits such as those of digital computers. Specifically, the project was to examine the feasibility of using miniature, standardized, plug-in transistor packages in a 370-tube data transmission set. By May 1951 Bell completed initial work and demonstrated the potential of point-contact transistors, which had an expected lifetime of 70,000 hours and yielded a fourfold reduction in volume and an eightfold reduction in power requirements over the tube version of the data set. The work produced two significant, concrete results. First, the eight reports for this contract provided the first published research on transistor applications to digital computers. Second, a later model of the data set became the first military equipment produced by Bell's manufacturing affiliate, Western Electric, using large numbers of transistors.[20]

Concurrent with this feasibility study, Bell also conducted a project for the Navy Bureau of Ordnance that may have been the first application of transistors. W.H. MacWilliams, Jr., an engineer trained at Johns Hopkins who had worked on fire control for the Navy during the war, successfully transistorized a component of a Bell simulated warfare computer in early 1949. The simulator used forty transistors, nearly all that were available at this early date.[21] MacWilliams's project prefigured the close interplay later to emerge between Bell's work on military systems and transistor development.

Two political events contributed to the military patronage of

19. Army Miniaturization Monograph, p. 118.

20. Bell Telephone Laboratories, "An Appraisal of Military Transistor Development, 1948–1957," 7 August 1957, n.p., copy in folder: Solid State Devices—Semiconductors, Subject Files Box 90, Bell Laboratories Archive (document hereafter cited as BTL Report, 1957). See also J. P. Molnar, "Military Applications of Transistors," speech given at press conference, 17 June 1958, copy in folder: Transistor—Tenth Anniversary, Lloyd Espenschied Collection, Bell Laboratories Archive; and Fagan, *History of Engineering and Science*, pp. 549–50. The activities within Bell between the initial military briefing and the signing of the first transistor contract deserve further study.

21. W. H. MacWilliams, "A Transistor Gating Matrix for a Simulated Warfare Computer," *Bell Laboratories Record* 35 (1957): 94–99.

the transistor. The National Security Act of 1947 centralized the military services under a new Secretary of Defense. The first secretary, James Forrestal, was confronted by a tradition of interservice rivalry, competition, and duplication. By creating a Research and Development Board under the secretary to supplant the ineffective Joint Research and Development Board, the act also attempted to improve the coordination of military research and development. As an arm of the Secretary of Defense, however, the board reflected the department's bureaucratic weakness. The board consisted of a civilian chairman and two representatives from each of the three services, and it operated through a complex web of committees and subcommittees. Further, it had no control over money and could only coordinate the projects that the services had already initiated.[22]

As elsewhere, the board's activities in the transistor field were loosely structured. An Ad Hoc Group on Transistors was organized in the summer of 1951. Chaired by a Bell vice-president, James McRae, the group was supposed to be a high-level body that would set broad policies for coordination of the transistor programs of the three services. It was joined shortly by a permanent Subpanel on Semiconductor Devices, but the group retained decision-making power. Although the military's transistor program was officially a joint service undertaking, the board's weakness permitted the Army Signal Corps to draw on its greater experience to become the military's center of transistor expertise. The Corps' prominence became manifest in 1951, when the Electronic Production Resources Agency, with the concurrence of the three services, assigned to it the responsibility of developing the new technology for military purposes.[23]

A second political event, the Korean War, strengthened Bell's ties to the military. This was demonstrated particularly in

22. Demetrios Caraley, *The Politics of Military Unification* (New York: Columbia University Press, 1966); Edwin A. Speakman, "Research and Development for National Defense," *Proceedings of the Institute of Radio Engineers* 40 (July 1952): 772–75; and Booz, Allen and Hamilton, Inc., *Review of Navy R&D Management, 1946–1973* (Washington, D.C.: Department of the Navy, 1976), pp. 16–25. For the administrative difficulties of the Research and Development Board, see Don K. Price, *Government and Science* (New York: New York University Press, 1954), pp. 144–52; and James L. Penick, Jr., et al., eds., *The Politics of American Science* (Chicago: Rand McNally, 1965), pp. 191–93.

23. I. R. Obenchain and W. J. Galloway, "Transistors and the Military," *Proceedings of the Institute of Radio Engineers* 40 (November 1952): 1287–88; and Army Miniaturization Monograph, p. 119. See also Jack A. Morton, copy of talk given to Generals Partridge and Doolittle, 7 January 1953, copy in binder: Semiconductor Devices—General, JAM Collection.

the work on air defense systems. In the closing months of World War II, the Army Ordnance Corps had asked Bell to study the feasibility of using ground-launched guided missiles against attacking bombers. By the outbreak of hostilities in Korea in 1950, Bell had nearly completed the design for the Nike air defense system, and the Army instituted a crash production program.[24] This expanded Nike program revealed a 250 percent increase in national military research and development expenditures between 1950 and 1953 (from $600 million to $1.6 billion).[25]

During the 1950s the military was also involved in a number of publicity efforts aimed at disseminating the new technology. As an explicit task of its second military transistor contract, Bell Laboratories held a symposium on transistor characteristics and applications at its headquarters in Murray Hill, New Jersey, in September 1951. Staff members presented twenty-five lectures and demonstrations to over three hundred representatives of the military services, universities, and electronics firms. Far from being an academic gathering, 139 industrial and 121 military personnel soundly outnumbered the 41 university representatives. In November the symposium proceedings appeared in a widely circulated 792-page volume. Each participant received a copy, the military services distributed 5500 copies at government expense, and Bell transistor licensees received an unknown number.[26]

A conference for Bell licensees in April 1952 disseminated more detailed information about the new technology itself.

24. Charles C. Duncan, "Communication and Defense," *Bell Telephone Magazine* 37 (Spring 1958): 16.

25. Arthur D. Little, *Basic Research in the Navy* (Cambridge, MA: Arthur D. Little, 1959) 1: 13. See also Samuel P. Huntington, "NSC-68 and Rearmament, 1950–1952," in *The Common Defense: Strategic Programs in National Politics* (New York: Columbia University Press, 1961), pp. 47–63; and Paul Y. Hammond, "NSC-68: Prologue to Rearmament," in Warner R. Schilling, Paul Y. Hammond, and Glenn H. Snyder, *Strategy, Politics, and Defense Budgets* (New York: Columbia University Press, 1962), pp. 267–378.

26. The Bell Telephone Laboratories report on the first conference listed the participants by name and institutional affiliation. No branch of the military services received preferential treatment either in attending the symposium or in receiving the published proceedings. See "Final Report on Task 3—Transistor Symposium," 1 February 1953, copy in an unmarked box in the Robert M. Ryder Collection, Bell Laboratories Archive. The general theme of the diffusion of technology has been most fully explored by Nathan Rosenberg; see his classic article, "Technological Change in the Machine Tool Industry, 1840–1910," *Journal of Economic History* 23 (December 1963): 414–43; and his collection, *Perspectives on Technology* (London: Cambridge University Press, 1976), pp. 141–210.

This conference, held at the urging of the military services and with funding from Western Electric, resulted in two fat volumes that became the canon of transistor technology (they were known within Bell as "the Bible"). As late as 1957 an internal Bell report described these volumes as "the first and still only comprehensive detailed treatment of the complete material, technique and structure technology." The same report noted that the information provided "enabled all licensees to get into the military contracting business quickly and soundly."[27]

Several factors account for the rapid assimilation of the new technology by the military bureaucracy. Because the Army Signal Corps had institutionalized the goal of miniaturizing electronic communications gear, it was primed for the announcement of the point-contact transistor. The transistor also complemented the Corps' new component-oriented mass production process. Finally, the rearmament effort following 1950 released new research and development funds for projects of military interest. These organizational, technological, and political factors combined to make the military a vigorous patron and promoter of the new technology. By sponsoring applications studies, organizing bureaus for production development, and disseminating the new technology to industry, the military assumed responsibility for presiding over the process of technological development and hence began its activities as an institutional entrepreneur in this new field. Much remained to be done with transistor development in the early 1950s. Before any large-scale production runs could be accomplished, a number of technical problems and manufacturing bottlenecks had to be overcome.

Technological Advances

By the end of World War II, scientists at Bell Laboratories had produced several metallurgical innovations that were to aid the invention of the transistor and exert an important influence in its subsequent development. First, J.H. Scaff and H.C. Theuerer had discovered that nearly pure silicon ingots could be prepared by melting silicon in a vacuum. These purified

27. BTL Report, 1957. See also the proceedings of military-sponsored conferences cited in notes 15 and 53.

ingots possessed a curious property: some would rectify current—that is, they would act as a one-way valve for the passage of electricity—only when they were in a negatively charged electrical field; others would do so only when they were in a positive field. Scaff and Theuerer named the former "n-type" and the later "p-type." Tipped off by a slight odor of phosphorus when the ingots were removed from the oven, the two metallurgists determined that extremely small amounts of impurities, below the level of spectroscopic detection, were responsible for the peculiar behavior. They found that elements on either side of the fourth column of the periodic table (the column that contains the semiconductors silicon and germanium) most actively produce the rectification effect. Elements from the fifth column, including phosphorus and arsenic, donate their excess electrons to the semiconductor's crystal lattice and make it n-type, whereas elements from the third column, including boron and indium, induce a deficit of electrons and make the crystal p-type. To prepare semiconductor materials for transistors, then, one simply had to dope a pure sample with a tiny amount of the desired impurity—approximately one atom in one hundred million. Using techniques developed at Bell by Gordon Teal and J.B. Little, one could grow a large single crystal (typically 8 cm. long and 2.5 cm. in diameter) from the doped sample. This crystal could then be diced into the small pellets needed for point-contact transistors.[28]

A refinement of the crystal-growing apparatus allowed the Laboratories to realize a radically new type of transistor. William Shockley had proposed the idea of a "junction transistor" early in 1948 and had elaborated its theory in a book, *Electrons and Holes in Semiconductors,* in 1950. A transistor consisting of three sandwiched layers of p- and n-type germanium was an elegant conception, but with the crystal-growing techniques then available, it simply could not be made. Not until 1951 did Teal and Morgan Sparks manage to modify their crystal-growing apparatus to accept pellets of impurities. This innovation made it possible to build Shockley's germanium sandwich. While a mechanical apparatus continuously pulled a solid bar out of a crucible of molten n-type germanium, it was doped

28. *Electronics* 53, pp. 223, 226; Slade, "Survey of Transistor Development (Part 1)," pp. 44–45; and Millman, *History of Engineering and Science,* pp. 417–22.

with a small amount of p-type impurity and then quickly re-doped with an excess of n-type impurity. The resulting n-p-n wafer in the bar was cut out and diced, and tiny leads were attached to its three regions, producing a "grown junction" transistor (figure 2). The key was the center layer, the "base," which controlled the passage of current across the device from the "emitter" to the "collector." Junction transistors had the advantage of relying not on the poorly understood surface phenomena that the point-contact transistor exploited, but on the less complex, better understood interactions of the two internal p-n junctions. They were also electronically less noisy and mechanically less fragile.

A year later work at General Electric and at the Radio Corporation of America yielded a second method of constructing junction transistors. Two p-type pellets were placed on opposite sides of a thin n-type wafer. When heat was applied, the pellets melted slightly into the wafer, producing an "alloy junction" transistor.[29]

Bell Laboratories announced two further advances in 1954. Purifying the semiconductor material had continued to be a problem, since the process required an extremely low level of impurities controlled to within a few percent. Purification was now greatly aided by the introduction of "zone refining," which Bell's W. G. Pfann had adapted from aluminum technology. Perfected after a three-year effort, the new procedure utilized the fact that impurities are more soluble in the liquid than in the solid phase. A heating apparatus slowly swept a narrow band of molten material across a horizontal bar of solid semiconductor material, carrying impurities to one end of the bar, which was then cut off. Zone refining could be repeated several times to reduce unwanted impurities to less than one part per billion.

The second major invention was the diffusion technique for manufacturing transistors. Junction transistors had been restricted to low-frequency uses because of difficulties in controlling their dimensions and, in particular, in reducing the thickness of the base layer of the triple-decker semiconductor

29. *Electronics* 53, p. 239; Robert M. Ryder, "Ten Years of Transistors," *Radio-Electronics* 29 (May 1958): 34; B.N. Slade, "Survey of Transistor Development (Part 3)," *Radio and Television News* 48 (November 1952): 69; Millman, *History of Engineering and Science*, pp. 575ff; and Shockley, "The Path to the Conception of the Junction Transistor."

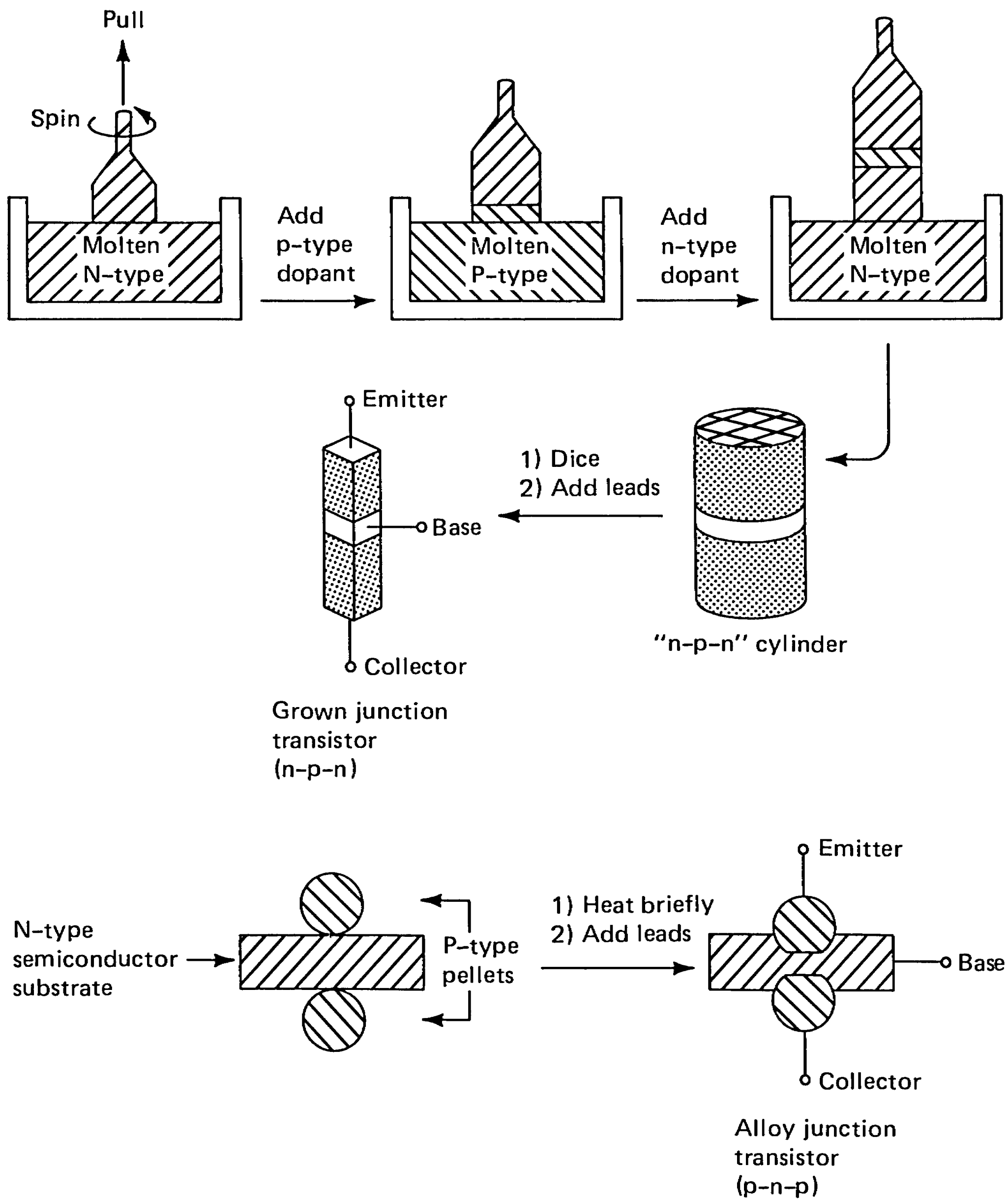

Figure 2
Fabricating junction transistors. Junction transistors were constructed by forming a three-layer sandwich of n-type and p-type semiconducting material. For grown junction transistors the layers were made while growing a large single crystal by adding a p-type dopant and then quickly redoping with an n-type dopant in excess. Alloy junction transistors were made by melting two p-type pellets onto an n-type substrate. In either method the center layer became the base, and the top and bottom layers became the emitter and collector. *Source:* R.L. Pritchard, *Electrical Characteristics of Transistors* (New York: McGraw-Hill, 1967), pp. 24–25.

sandwich. The diffusion technique solved this problem by exposing a solid semiconductor substrate to an atmosphere of vaporized doping agents, which by diffusing into the substrate produced a very thin surface layer. By carefully controlling the temperature and the duration of the exposure, the thickness of the transistor's layers could be dramatically reduced and, more important, precisely controlled. Diffusion technology extended the maximum frequency germanium transistors could amplify by approximately two orders of magnitude, from 10 to 1000 million cycles per second. The new manufacturing technique thus created a family of well-understood transistors capable of amplifying high frequencies.[30]

By the mid-1950s, then, transistors were no longer fragile laboratory curiosities. Innovations in metallurgical techniques and solid-state theories had allowed Bell Laboratories to build the first junction transistor. This new device had many specific forms, and all shared the advantages over point-contact transistors of being better described by contemporary physical theories, electronically less noisy, and mechanically more robust. Further, the new diffusion technology produced transistors that could amplify high frequencies and be mass produced. These advances, in turn, made practical the emerging efforts to build a large production capacity for the new technology.

Industrial Mobilization

The problem of procuring adequate numbers of transistors persisted well into the 1950s. Although the transistor appeared promising to many people, as indicated by the interest in the Bell symposia, its potential could not be realized until researchers had a sufficient supply to allow experimentation, the building of prototypes, and the manufacture of electronic equipment. Because of the clear military importance of the transistor and because the services were generally concerned with ensuring a war-ready industrial base,[31] the military under-

30. Ryder, "Ten Years of Transistors," pp. 35–37; Millman, *History of Engineering and Science*, pp. 423–28, 597–600; Jack A. Morton, "Bell System Transistor Program," 1958, copy in binder: Papers and Talks, JAM Collection; and Jack A. Morton and William J. Pietenpol, "The Technological Impact of Transistors," *Proceedings of the Institute of Radio Engineers* 46 (June 1958): 955–59.

31. See Seymour Melman, *The Permanent War Economy* (New York: Simon and Schuster, 1974); and Robert D. Cuff, "An Organizational Perspective on the Military-Industrial Complex," *Business History Review* 52 (Summer 1978): 250–67. For

took to help build a national production capacity for this technology. Not only did they increase their research and development contracts and their procurement, but they also started to underwrite the construction of private manufacturing facilities.

Again, the Army led the way. Two Signal Corps officers wrote revealingly in 1952 of the military's interests in the new technology:

> In more normal times the military services would embark on only a modest program of "transistorization" leaving the broad general problem of the maximum utilization of these devices to the ingenuity of our industry and research institutions. Now, however, in this period of international tension the services consider the possible benefits of transistors to military equipments [sic] as sufficient to warrant substantial programs in this field and to include concurrently not only research and development, but the planning and preparation of facilities for producing large quantities of these devices.[32]

Military support of transistor research at Bell rose from a small level in 1950 to 20 percent of total funding in 1952 and to 50 percent in 1953, a level sustained through 1955. Bell's second military contract, signed in May 1951, also provided for an expanded role for military priorities. Whereas the first contract had been limited to application and circuit studies, the second specified that services, facilities, and materials were to be devoted to studies of military interest, while work continued on applications and circuits.[33]

Bell now began to coordinate transistor development with military requirements. Indeed, Bell's military systems laboratory at Whippany, New Jersey, would generate most of the military projects for which transistors were required. Under this contract, Bell and the military services jointly chose to de-

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technological change in this political context see Kent C. Redmond and Thomas M. Smith, *Project Whirlwind* (Bedford, MA: Digital Press, 1980); and Clayton R. Koppes, *JPL and the American Space Program* (New Haven: Yale University Press, 1982).

32. Obenchain and Galloway, "Transistors and the Military," p. 1288. Lt. Colonel Obenchain was Assistant to the Commanding Officer for Research, SCEL; First Lieutenant Galloway was a member of the Office of the Director of Research of the SCEL.

33. From 1948 to 1957 Bell's transistor development program cost $22.3 million, 38 percent of which was funded by the military. During this period, Bell spent an additional $12.5 million of its own funds for physical, chemical, and metallurgical research in areas related to semiconductors. BTL Report, 1957.

velop twelve electronic prototypes for military systems.[34] Coordinating the development of devices to match the requirements of specific military systems proved a task that would tax the resources and organization of the Laboratories throughout the 1950s.

Significantly, at this same time Bell was experiencing difficulties in introducing transistors into the telephone system. In the fall of 1952 the Laboratories conducted a trial installation of transistorized direct-dial switching equipment in Englewood, New Jersey; and the first all-transistor telephone system was tested a year later in rural Georgia. Nevertheless, Mervin Kelly urged caution. "The transistor," he conjectured, "will come into large-scale use in the Bell System only gradually. Other fields of application—military electronics systems, home entertainment, special services—may well have the larger initial uses."[35] As a carefully integrated complex of sophisticated electronic equipment, the telephone system could add transistors only as old equipment was retired and as the newcomer demonstrated its reliability and economy. Rural telephone systems, which previously were without vacuum tubes or other amplifiers, were now the first systems to be transistorized, and it was not until the early 1960s that transistors were in large-scale use throughout the telephone system.[36]

High cost also severely constrained civilian applications of transistors. Commenting on the "discouragingly slow" introduction of the new technology into the telephone system, Jack Morton, Bell's director of transistor development, wrote: "Even though we realize the larger complexity of Bell systems as a contributing factor, we are impressed with the fact that economic difficulties, particularly the cost of components, looms as a large factor in this situation."[37] When Raytheon introduced one of the first transistor radios in 1955, the firm gave it a price of $80 and aimed promotion at the luxury market. Hearing-aid users formed one group willing to pay for the

34. Ibid. The twelve prototype devices are described in this report.

35. Kelly, "The First Five Years of the Transistor."

36. For example, the total value of the Bell System's transistorized equipment by 1963 had reached only $150 million—approximately 5 percent of the annual sales of Western Electric, the manufacturing branch of AT&T. See Jack A. Morton, "Application of Transistor Technology to the Bell Communications System," copy in binder: Material Prepared and Used by J. A. Morton in connection with British Patent Case, JAM Collection.

37. Morton, "Bell System Transistor Program," p. 20.

transistor's small size and low power requirements. The first hearing aid, with two vacuum tubes and one transistor, sold for a smart $229.50.[38] Military users were also ready to meet the steep costs of the new device in order to obtain its notable advantages. Unlike the hearing-aid users, however, the military services could afford to help pay the developmental costs needed for increased production.

The Army employed three related strategies to build up a large production capacity for transistors. One was to finance new plants directly. In 1953, for example, the Signal Corps underwrote the construction of a huge Western Electric transistor plant at Laureldale, Pennsylvania. Altogether the Army spent nearly $13 million in underwriting the construction of pilot plants and production facilities. In addition to Western Electric, General Electric, Raytheon, Radio Corporation of America, and Sylvania benefited from such military support.[39]

A second Army program stressed engineering development. Whereas work at the fundamental level of development translated concepts and inventions into usable prototypes, engineering development carried these prototypes to the point where they could be manufactured in production quantities efficiently and economically. The Army intensively funded this industrial mobilization effort. Before 1956 the Signal Corps' contracts for research and fundamental development in semiconductors—with Bell Laboratories alone before 1955, and thereafter also with Radio Corporation of America and Pacific Semiconductor—averaged $500,000 annually. After 1956 these contracts averaged approximately $1 million annually. In comparison, for the more expensive process of engineering development, the Army let contracts from 1952 to 1964 totaling $50 million, for an annual average of over $4 million.[40]

A third Army initiative influenced the cohesion of the emerging transistor industry. In mid-1953 the Signal Corps sponsored a conference aimed at standardizing the operating characteristics of transistors. The details were hammered out in meetings with representatives of the Navy and Air Force, leaders in the industry, and the Radio Electronics Television Manu-

38. See "Transistors: Growing Up Fast," *Business Week* (5 February 1955): 86; *New York Times*, 14 January 1953, 18 March 1954; *Wall Street Journal*, 17 April 1953; Bello, "The Year of the Transistor," p. 132.

39. Bello, ibid., p. 129.

40. Army Miniaturization Monograph, pp. 116, 128–30.

facturers Association.[41] Historians have evoked both practical and ideological factors to explain the military's frequent efforts to standardize procedures and technology.[42] In this case, the complexity of the electronic systems for which transistors were developed suggests a compelling objective reason for the Signal Corps' initiative. Nevertheless, the standardization of components for transistor circuitry was limited throughout the 1950s because the industry was unable to agree on standard shapes and sizes, and firms in turn were reluctant to invest in new production tooling in the absence of such consensus.[43]

The overall effects of the military's wide-ranging support were pronounced but complex. In its role as an institutional entrepreneur presiding over technological change, the Army undoubtedly increased the pace of transistor development. Historians Ernest Braun and Stuart MacDonald have even argued that military support produced a sizable overcapacity. In 1955, for example, 3.6 million transistors were manufactured in the United States, yet the industry's capacity was over four times larger: 15 million units.[44] Placing these production figures in their national political context helps to resolve this anomaly. Seymour Melman's thesis that in the years following World War II the American defense industry remained in a state of permanent mobilization for war suggests an explanation for these figures.[45] Even though the excess capacity wasted production capital, it was there for rapid mobilization in the event of a large-scale war. Although this strategy may have served the military's program, the cost- and resource-conscious electronics industry moved in the late 1950s to coordinate supply more closely with demand.

41. *Electronics* 53, p. 240.

42. See Lewis Mumford, *Technics and Civilization* (New York: Harcourt, Brace and World, 1934; reprinted 1963), pp. 84–96; and Merritt Roe Smith, "Military Entrepreneurship," in O. Mayr and R. C. Post, eds., *Yankee Enterprise: The Rise of the American System of Manufactures* (Washington D.C.: Smithsonian Press, 1981), pp. 63–101, revised and reprinted as the first essay in this volume.

43. Army Miniaturization Monograph, p. 150.

44. Braun and MacDonald, *Revolution in Miniature,* p. 81.

45. Melman, *The Permanent War Economy.* For difficulties in mobilizing the war economy during World War II, see Alan S. Milward, *War, Economy and Society* (Berkeley: University of California Press, 1977); and William M. Tuttle, "The Birth of an Industry: The Synthetic Rubber 'Mess' in World War II," *Technology and Culture* 22 (January 1981): 35–67.

Military Requirements and Technological Development

By 1954 the transistor development effort at Bell had shifted to an emphasis on applications. In March Jack Morton observed that "over the last year and one-half, Bell Laboratories systems applications have grown at an almost explosive rate."[46] Figure 3 shows the striking increase in the circuit and systems development staff from 1951 to 1954. More important, the earlier dependence on the military transistor market appeared to be ending. "When last year's forecast for 1954 and beyond was made," Morton continued, "Military items accounted for the bulk of the orders even through 1956. . . . However, this year's forecast can be seen to depend almost entirely on Bell applications."[47] The updated forecast indicated the requirements of the Bell System for transistors during 1955 would eclipse those of Bell's military projects by a factor of ten. Two large telephone projects alone, Rural Carrier and Line Concentrator, accounted for 500,000 transistors in 1955 and over one million in 1956. By contrast, Bell's total military transistor sales were scheduled to be 60,000 in 1955, increasing to only 175,000 in 1956. It appeared the extensive use of transistors predicted by Mervin Kelly in 1940 was finally a fact. But events at Bell during 1955 were to revise the optimistic forecast of the previous year and reemphasize the role of the military in transistor development. This continued presence extended the military's entrepreneurial influence beyond presiding over the development process. Military enterprise now began to shape the style of the technology.

Bell Laboratories had several reasons to be wary of dependence on military patronage. One was the unreliability of military contracting. For example, in November 1952 the Laboratories had begun designing a solid-state photosensor for the Naval Research Laboratory (NRL). By December 1954 Bell had delivered nine prototypes to the Navy and had completed the contract except for final engineering development. Although Bell scientists felt that the prototypes fully met the stringent electrical and mechanical specifications, the NRL abruptly dis-

46. Bell Telephone Laboratories, "Semiconductor Devices: Research and Development Report—March 5, 1954," n.p., copy in binder: Semiconductor Devices, Box 67, Bell Laboratories Archive (document hereafter as BTL R&D Report, 1954).

47. Ibid.

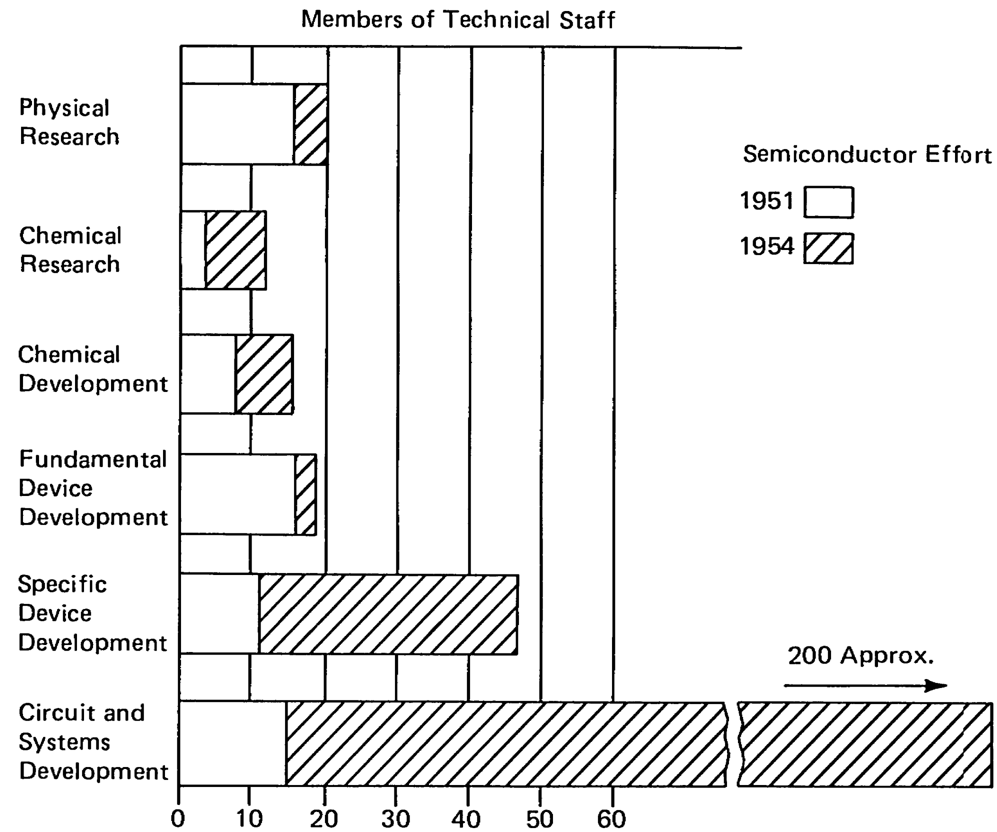

Figure 3
Bell Telephone Laboratories semiconductor effort 1951 and 1954. *Source:* Bell Telephone Laboratories, "Semiconductor Devices: Research and Development Report—March 5, 1954," Bell Laboratories Archive.

continued the project for unclear reasons. Aside from the waste of time and resources, morale suffered when two years of effort were discarded without explanation. A second related reason for caution was the instability of the military transistor market. As table 2 shows, Western Electric's production for military applications fluctuated wildly throughout the 1950s. Cost reductions were difficult to achieve under such conditions because the uneven production runs required frequent changes in tooling, leading to additional expenses and unproductive down time.[48]

After 1955 Bell's problems with the Army centered on difficulties with the development of the Nike II antiballistic missile system. The Army's air defense program had shifted from its post-World War II concern with enemy bombers to

48. BTL Report, 1957, see "Task 6." For further difficulties with the military transistor market, see Jack A. Morton, "Military Device Development," 1958, copy in binder: Papers and Talks, JAM Collection.

Table 2
Transistors and diodes for military applications manufactured at Western Electric plants at Allentown and Laureldale, Pennsylvania

Year	Total Military Diodes	Total Military Transistors
1952	196,800	35,200
1953	96,500	75,700
1954	220,200	146,200
1955	143,000	44,800
1956	179,000	166,300
1957 (first 6 months)	258,800	36,500

Source: Bell Telephone Laboratories, "An Appraisal of Military Transistor Development—1948–1957," 7 August 1957, Subject Files, Box 90, Bell Laboratories Archive, Short Hills, New Jersey.

building a system that would guard against attacks by long-range missiles. In February 1955 the Army Ordnance Corps asked Bell to begin planning a major new missile system. The Whippany military systems laboratory immediately began work on the Nike II, a program that resulted in the design of the Nike-Zeus and Nike-X missiles. The project lasted for twenty years and was "the largest and most extensive program in depth and breadth of technology carried out by the Bell System for the military services."[49]

Unlike the original Nike study of a decade earlier, the Nike II program began when the transistor's small size and low power requirements were readily available. The transistor development staff was already overextended and could take on new projects only at the expense of current ones. Although the number of staff members working on applications had increased dramatically from its level in 1951, Morton still complained of a shortage of development engineers and of a "serious curtailment of fundamental development."[50] To alleviate the problem he recommended that forty-four more engineers and scientists be added to the development team. He

49. Fagan, *History of Engineering and Science,* p. 394. On the original Nike project see 370ff. and on the Nike II and its subsequent projects see 394ff.

50. Morton identified three long-range problems: "(1) For any given specific device there may be a number of alternate technologies which might be used. Lack of fundamental analytical technology development forces the project engineer to choose a technology purely on an expediency basis. (2) Lack of device manpower and lack of fundamental analytical technology work prevents the rapid exploration of new and promising structures. . . . (3) Exploration of the device applications of new materials, even silicon, is lagging and our competitive bargaining position may be challenged seriously." BTL R&D Report, 1954.

also warned that "any rescheduling of military devices will require rescheduling of large blocks of major systems in both Bell and Military areas. This should only be done," he added, "if it can be proved that the new devices are much more urgently needed for actual major military systems work."[51] In fact, one of the two major telephone projects was cancelled during this period. Although this project was already in trouble because of its high cost, the demanding work on Nike II almost certainly hastened its demise.

In addition to complicating the application of transistors to the Bell telephone network, the effort to coordinate device development with military systems work significantly influenced the style of the emerging technology. The high performance requirements of military electronics systems exacted the utmost from their components, and the transistor was no exception. An examination of specific characteristics of the transistors the military chose to promote reveals the tension between military performance and commercial economy.

Military applications frequently required electronic components to withstand high temperatures.[52] The ambient temperature within jet aircraft and guided missiles, for example, often exceeded 75° C, the maximum operating temperature for germanium transistors. Equally important, military applications required the equipment to be of the small size so easily achieved by using solid-state devices. Consequently, silicon transistors, with a maximum operating temperature above 150° C, sold briskly to the military services, despite their much higher cost as compared to germanium transistors. The military's preference for silicon transistors allowed their chief manufacturer, Texas Instruments, to carve out a niche in the semiconductor market.

A secondary reason for the military interest in silicon devices was their resistance to radiation. With the expansion of the Navy's nuclear-powered fleet and the Air Force's plans to develop a nuclear plane, the procurement of transistors able to withstand radiation became a stated goal.[53]

51. Morton, "Bell System Transistor Program." Quote from BTL R&D Report, 1954.

52. Two Signal Corps officers had noted in 1952: "The large variation with temperature of the present type of transistors' [operating characteristics] is . . . of particular difficulty since so many military equipments require operation over extended temperature ranges." Obenchain and Galloway, "Transistors and the Military," p. 1288. See also George R. Spencer, "Transistors: Past, Present, Future," *Radio-Electronics* 29 (May 1958): 40.

53. For Navy needs see W.I. Bull, "Transistor Reliability and Military Requirements,"

But what the military wanted most was a transistor capable of amplifying high-frequency signals. High-frequency radios, high-speed data transmission equipment, and high-speed computers all required high-frequency amplifying devices. The use of transistors would allow dramatic reductions in size, weight, and power requirements.[54] Because junction and point-contact transistors simply could not fulfill this need, the Signal Corps strongly supported the development of new types of devices. For example, in 1954 researchers at Bell invented the intrinsic barrier transistor in a project supported by its Signal Corps contract. This exotic four-layer device was so named because the fourth layer formed an internal barrier that supported the base layer of the semiconductor sandwich, whose thickness controlled the high-frequency response. This allowed the base to be made much thinner without breaking down at high voltages. Even though this device was difficult and expensive to manufacture, it was used in several military applications.

The diffusion process described above was the real breakthrough in high-frequency devices. The Signal Corps' support of diffusion research at Bell was striking. Indeed, in the late 1950s, the Signal Corps' support of fundamental transistor development exceeded Bell's own in-house support in only a few cases, and all of these were devices produced by the diffusion process.[55] Moreover, the Signal Corps coordinated its support to push the new technology from fundamental development into manufacture. In late 1955, when Bell released the diffusion process to industry,[56] the Signal Corps was ready with a hefty dose of engineering development funds for those who

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and for Air Force needs see Palmer E. Koenig, "Transistor Reliability and Air Force Requirements," in *Proceedings of the Transistor Reliability Symposium,* sponsored by the Working Group on Semiconductor Devices of the Advisory Group on Electron Tubes. Office of the Assistant Secretary of Defense Research and Engineering, 17–18 September 1956 (New York: New York University Press, 1958).

54. BTL Report, 1957, see "Task 4"; and Ryder, "Ten Years of Transistors," pp. 36–37.

55. Morton, "Military Device Development," pp. 6–7.

56. Political considerations, in the form of an ongoing antitrust suit, persuaded Bell to release its technology to industry quickly in order to avoid appearing to monopolize the transistor field. The Justice Department had initiated a suit against AT&T in 1949 with aims of splitting Western Electric away from AT&T. The proceedings were halted in 1956, however, when AT&T agreed to several concessions. One was being enjoined from selling semiconductor devices on the commercial market (the military and space markets, as well as the Bell System, remained open); another was that Western Electric was forced to license all its existing transistor patents with minimal royalties. See Tilton, *International Diffusion,* pp. 50, 76.

would undertake to manufacture transistors. In fiscal year 1956 the Corps placed the largest engineering development contracts up to that time, totaling over $15 million. Nearly all the semiconductor firms in the country participated. A Corps historian noted that the program's purpose 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."[57]

The Signal Corps was not the only service interested in diffusion technology. This became evident in a Bell program to identify "preferred devices" whose development was to be expedited. The purpose of this program was to combat the rapid proliferation of transistor types that marked the mid-1950s. Whereas in 1953 there were 60 different types of transistors, by 1956 there were 275, and by 1958 there were more than 900.[58] This variety greatly complicated the development of large-scale military systems. Each manufacturer would supply several transistor types, and integrating these into the same system often proved difficult. To streamline the Laboratories' work, W.C. Tinus and R.R. Hough, managers of the Nike program with extensive experience in military systems engineering, appointed a committee to address the possibilities for standardization. The committee's report, issued in July 1957, called for the creation of a Military Semiconductor Program to expedite the development of transistors needed specifically for military systems. The program was quickly enacted and several computer and missile projects, including Nike II, received this special attention. Describing the military's priorities, Morton observed that the preferred transistors were all diffused. These included germanium transistors for high-frequency service and silicon devices to meet high-temperature requirements.[59]

57. Army Miniaturization Monograph, pp. 125, 130.

58. Gernsback, "Transistor Trends," p. 33; and Spencer, "Past, Present, Future," p. 39.

59. Morton, "Military Device Development," pp. 14–17. The committee was chaired by E.H. Bedell; its other members were heads of transistor development projects. The family of "preferred devices" was designed to: "(1) Meet the performance and reliability requirements of military systems, (2) Gain wide acceptance and use such that the manufacturing level would be high with the resulting economies in manufacture, and (3) Be made available on a stockroom basis to provide early support of systems development." Uses for the preferred devices included, "Stretch," a military project on high-speed computers at the University of Illinois; "Lightening," a military-directed computer research project done by Remington-Rand Univac designed to produce the ultimate in high-speed computers; several military projects of Bell Telephone Laboratories, including the Ballistic Missile Early Warning System (BMEWS) and the Nike-Hercules and Nike-Zeus missiles; the inertial guidance system developed by ARMA for

Bell's Military Semiconductor Program received favorable attention from other firms, and the Laboratories soon moved to implement a similar program to streamline transistor development for Bell System applications. To this end, Walter A. MacNair, a former director of military systems engineering and vice-president of the Bell-affiliated Sandia Corporation,[60] organized in February 1958 a "Preferred Codes" program. Like its counterpart for military applications, this program required extensive cooperation between those engaged in development work and those concerned with applications. MacNair appointed a committee of division chiefs chaired by J.J. Ebers, the head of Device Development who had also served on the original committee that designed the Laboratories' Military Semiconductor Program, to carry out the program. Comparing the preferred transistors of the military with those of the Bell System, Morton noted that the Bell list included several types of alloy germanium transistors. "Unlike the Military applications," Morton explained, "there are a large number of Bell System applications which do not require the high-performance diffused devices." He concluded with an important point concerning the relative need for diffused devices. Even though the preferred list for Bell System applications included diffused germanium devices, Morton forecasted that Bell would need only small numbers of them. In contrast, he expected diffused transistors to be used in large numbers for military applications, "primarily because of the very high switching speeds required in Nike-Zeus."[61]

The production figures for diffused transistors demonstrate the accuracy of Morton's report. By the end of 1958 Western Electric had manufactured 171,000 diffused transistors for military applications, but *none* for consumption by the Bell System (see table 3). The close coordination of device development with military systems work had effectively translated military performance needs into manufactured devices, but at the same

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the Atlas and Titan missiles; and the Polaris submarine-launched missile system. For information on Hough and Tinus, see Fagan, *History of Engineering and Science,* pp. 24, 400–401, 676, 690, 697.

60. The Sandia Corporation was a former branch of the Los Alamos Scientific Laboratory that the University of California had divested in 1949. Sandia was owned by the Atomic Energy Commission and managed by Bell executives. See Fagan, ibid., pp. 650ff.

61. Morton, "Bell System Transistor Program," pp. 8–11.

Table 3
Total transistors manufactured by Western Electric through 1958 by type and application

Transistor Type	Application: Military	Bell System
Point Contact	291,000	259,000
Grown Junction	115,000	265,000
Alloy Junction	116,000	98,000
Diffused Germanium	145,000	–
Diffused Silicon	26,000	–
Total	693,000	622,000

Source: Jack A. Morton, "Bell System Transistor Program," p.1, Jack A. Morton Collection, Bell Laboratories Archive, Short Hills, New Jersey.

time it had complicated and perhaps even compromised Bell's overall production efficiency.

Military Enterprise and Technological Style

The activities of the military services, specifically the Army Signal Corps, during the late 1940s and throughout the 1950s had several notable effects on the emerging transistor technology. A close-working combination of industrial firms and military agencies presided over the development phase of this technology. If industry's strengths were technological, the military's were organizational. Military-sponsored conferences and publications rapidly disseminated the new technology to industry. Moreover, by subsidizing engineering development and the construction of manufacturing facilities and by leading the movement to standardize operating characteristics, the military catalyzed the establishment of an industrial base. Finally, military requirements for transistors that could withstand high temperatures and amplify high frequency signals promoted the development of certain types of high-performance devices, including silicon transistors and transistors constructed by diffusion technology. The Army Signal Corps not only underwrote the fundamental development of this technology, but also, as soon as it was released to industry, expedited the translation of prototypes into manufacturing processes and devices by strongly supporting engineering development.

In addition to presiding over the development process, the military services contributed notably to the technology's eventual shape and style. As the electronics industry moved into the 1960s, the cost of transistors came down and, consequently, commercial sales rose and eventually surpassed military sales. Although it might be tempting to conclude that military patronage had merely allowed the technology to mature until costs could be reduced, this simplistic "pump priming" interpretation needs to be examined closely.[62] As the case of the Signal Corps' intensive promotion of the high-performance diffused transistor illustrates, military patronage could be tightly tied to specific variants of the new technology that filled requirements virtually unique to the military. Further, the subsequent development of solid-state technology suggests that military patronage has had several enduring aspects. A complex of characteristics suggesting a technological style, including the structure of the industry and the technology appearing at its cutting edge, were linked to the military in the 1950s and have continued to be associated with military enterprise.

The structure of an industry significantly contributes to its technological style. One specific characteristic of use to historians is standardization. Examining when the specifications for a technology are standardized on a national basis, and by whom, emphasizes the technology's cultural context. For the American transistor industry, the military services orchestrated standardization relatively early, in mid-1953. In contrast, the British semiconductor industry remained without national standards until the 1960s.[63] The attempts to designate preferred devices needed for specific projects at Bell Laboratories in the late 1950s was another milestone in standardization. Significantly, it was Bell managers who had had extensive experience with complex military projects who initiated these programs, first for the Laboratories' military systems and then for those of the Bell System itself.

62. The pump-priming model is maintained by Norman J. Asher and Leland D. Strom, "The Role of the Department of Defense in the Development of Integrated Circuits," Institute for Defense Analyses Report P-1271, May 1977, available from NTIS, Springfield, VA, as report No. ADA048610; and Air Force Systems Command, *Integrated Circuits Come of Age* (Washington, D.C.: Air Force, 1966). A more sophisticated view informs Daniel P. Jones, "From Military to Civilian Technology: The Introduction of Tear Gas for Civil Riot Control," *Technology and Culture* 19 (April 1978): 151–68; and John H. Perkins, "Reshaping Technology in Wartime: The Effect of Military Goals on Entomological Research and Insect-Control Practices," ibid., pp. 169–86.

63. See Jerome Kraus, "The British Electron-tube and Semiconductor Industry, 1935–62," *Technology and Culture* 9 (October 1968): 544–61.

Examining the cutting edge of an emerging technology and the interests pushing its development provides another clue to the cultural context shaping technological style. Military patronage of the most technically sophisticated, high-performance semiconductor technology has been a recurring pattern in the United States. When coupled to the development process, military needs promoted the high-performance diffused transistor in the 1950s, the integrated circuit in the early 1960s, and the very-high-speed integrated circuit in the early 1980s.[64] The driving force behind the semiconductor industry in Japan, in contrast, has been the powerful Ministry of International Trade and Industry (MITI). In electronics MITI has emphasized not ultra-high-technology product lines but rather the large-scale, coordinated expansion of the semiconductor market.[65]

If the American military's entrepreneurship did in fact increase the overall rate of development of the transistor, this increase was not achieved without cost.[66] Bell Telephone Laboratories in particular felt acutely the tension between military performance and commercial economy. Even though the transistor had been invented for use in the telephone system, this use was realized only in the early 1960s. In part, Bell Laboratories' military transistor work throughout the 1950s compromised this effort by draining manpower from development work on Bell System applications. Scientists and engineers with experience in the new field were a valuable resource and could not be replaced at will.[67] Further, since the specific characteristics of the transistors developed for military applications were

64. For a military view of these developments, see Asher and Strom, "The Role of the Department of Defense" and Air Force Systems Command, *Integrated Circuits Come of Age*. On military support of very-high-speed integrated circuits, see Robert DeGrasse, "The Military and Semiconductors," in J. Tirman, ed., *The Militarization of High Technology* (Cambridge, MA: Ballinger Publishing Co., 1984), pp. 77–104; and *Science* 219 (11 February 1983): 750. For speculation on the next generation of military support of ultra-high technology, see "Nanocomputers from Organic Molecules?" *Science* 220 (27 May 1983): 940–42.

65. Chalmers Johnson, *MITI and the Japanese Miracle: The Growth of Industrial Policy, 1925-1975* (Stanford: Stanford University Press, 1982).

66. I use the term "cost" here in the economist's sense of "opportunity cost," referring to an opportunity foregone or postponed.

67. Concern remains on the part of science policy analysts about the adverse effects of the military's draining of technical personnel from commercial applications; see Michael Schrage, "Defense Budget Pushes Agenda in R&D," *Washington Post*, 12 August 1984, p. Fl. For an informed discussion of the current problems of U.S. electronics, see Charles H. Ferguson, "The Microelectronics Industry in Distress," *Technology Review* 86 (August–September 1983): 24–37.

frequently different from those developed for the Bell System, the spillover from military to commercial uses was incomplete at best.

The style of high-technology innovation illustrated by the transistor has been an enduring force in the postwar era. In areas as diverse as computer graphics, artificial intelligence, and numerically controlled machine tools, military enterprise has significantly altered the technological landscape.[68] In setting priorities for research and development, serving as a large consumer of new products, and influencing the structure of an entire industry, the military has become a de facto architect of high technology policy. This mission-agency style of innovation has entailed selecting specific variants of emerging technologies. By definition this has biased technological change. If pervasive, the distinction between military performance and commercial economy has not been absolute. For the transistor, neither design criterion, performance, nor economy, completely dominated the other. Rather, these two technological characteristics formed a complex matrix of possibilities and outcomes that shaped the development of this important technology.

68. See Tirman, *The Militarization of High Technology;* and David Noble's essay in this volume.