Strategic Management Journal
Strat. Mgmt. J., **21**: 1017–1041 (2000)

THE NATURE, SOURCES, AND CONSEQUENCES OF FIRM DIFFERENCES IN THE EARLY HISTORY OF THE SEMICONDUCTOR INDUSTRY

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Four entrants into the early semiconductor industry—Sprague Electric, Motorola, Shockley Semiconductor Laboratories, and Fairchild Semiconductor—displayed remarkably different performance and behavior. Case studies of the firms demonstrate that the key differences stemmed from the firms' technological goals and activities and their abilities to integrate R&D and manufacturing. These differences can in turn be related to the firms' origins and their different conditions upon entry into the semiconductor industry, which had lasting effects due to constraints on change. While the cases offer limited prescriptions for management, they underscore the importance of technological diversity for an industry's rate of technical advance and, in turn, public policies that support such diversity. Copyright © 2000 John Wiley & Sons, Ltd.

INTRODUCTION

Corporate strategy is centrally concerned with the characteristics of firms that condition performance. Related notions of firm capabilities, core competences, dynamic capabilities, and intangible assets have been invoked to help firms identify their unique, inimitable qualities and devise a business strategy to exploit them (cf. Rumelt, Schendel, and Teece, 1994). Spurred by policy and theoretical concerns and access to establishment census data, economists have also examined intraindustry firm differences, focusing on profitability and behaviors such as entry, exit, innovation, and advertising (e.g., Ravenscraft, 1983; Schmalensee, 1985; Mueller, 1986; Rumelt, 1991; Cohen and Klepper, 1992; Geroski, 1995; Jensen and McGuckin, 1997; Caves, 1998). Economists have found firm behavior and performance to be quite heterogeneous, although robust findings have not yet emerged on the sources of the heterogeneity. The strategy literature is also voluble on the sources of within-industry differences in performance, but it too does not offer robust findings.

In this paper, we step back from both the management and economics literatures on intraindustry firm differences to consider some basic questions. For example, how do firms in an industry differ, and how do the differences affect behavior and performance? What are the sources of the differences? How are they influenced by managers' decisions? These issues are relevant to scholars of management in their attempts to prescribe what firms need to do to achieve superior performance. While economists tend to be more concerned with the performance of industries as a whole than individual firms, differences in the products and problems that firms work on may also affect the long-run performance of industries. They also raise questions about whether markets, left to themselves, are likely to spawn a socially desirable degree of firm heterogeneity.

Key words: firm capabilities; innovation; evolution

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However fundamental, these questions concerning firm differences are not easy to address. We thought it possible to make some limited headway by exploiting the detail and richness of a recent historical study of the experiences, activities, and performance of four firms in the early semiconductor industry (Holbrook, 1999). The firms include: Sprague Electric Company, a producer of electronic components; Motorola Incorporated, a manufacturer of telecommunications equipment and systems; Shockley Semiconductor Laboratories, a start-up created by a co-recipient of the Nobel prize in physics for the invention of the transistor; and Fairchild Semiconductor Corporation, also a new firm set up by eight defectors from Shockley. These firms were chosen based on the availability of data and their diverse backgrounds and fates. Shockley failed relatively quickly. Sprague prospered for a time and made important contributions to technical advance before it exited. At first immensely successful, Fairchild contributed innovations of great importance and, when it stalled, several of its founders and employees left to form many of the firms that populate the industry today. Motorola steadily expanded its operations in semiconductors and continues to prosper, though even it has faced major challenges at several junctures.

Using archives, interviews, published and unpublished accounts by insiders, and secondary sources, we reconstruct the backgrounds of the four firms and how they addressed the challenges they faced during the early years of rapid technological change in the semiconductor industry. We examine the firms' perceptions of opportunities in the industry, their capabilities, decision-making processes, and the technical and business choices they made. We use this examination to reflect on hypotheses regarding the nature and role of firm capabilities developed by scholars of management and economics. We also analyze the impact of firm differences on the rate of technical advance for the industry, a central concern of industrial organization scholars working from an evolutionary perspective (e.g., Nelson, 1991).

For each of the firms, we provide highly condensed versions of the histories presented in Holbrook (1999).[1] These histories delimit the questions we address. We lay out these questions in the next section. We then recount the origins of the semiconductor industry and present the four firm histories. In the following section, we use the firm histories to reflect on the questions raised. In the last section, we discuss the implications of our reflections for firm strategy and public policy.

LITERATURE AND THEORY

The nature, sources, and consequences of firm differences within industries have been addressed at some length—and in greatest detail—in the recent strategy literature. In this section, we briefly review some of the key hypotheses and insights from this and related literatures. Our review is selective, guided by the questions we can address based on the firm histories.

We begin by examining the conditions associated with the entry of the four firms into the industry. While conventional economics is silent regarding the particular features of firms that motivate entry into an industry, the strategy literature's resource-based view of the firm stresses the importance of pre-existing know-how, often termed 'intangible assets,' in guiding what firms do. This suggests that firms entered the semiconductor industry at least partly to leverage their know-how, which for established firms refers to know-how previously developed for purposes that did not anticipate the emergence of the semiconductor industry. Similarly, *de novo* firms might be envisioned as entering to leverage assets that their principals previously assembled. This raises questions about whether the pre-entry assets of pre-existing and *de novo* firms—especially know-how—explain the timing of entry, initial market positioning and product mix, and the range of options, both perceived and truly available, to entrants at the time of entry.

If existing know-how influenced firms' entry decisions, did it also influence the firms' subsequent behavior and performance? Did it affect the types of R&D projects they undertook as well as the particular products they produced? Once again, conventional economics postulates little link between firm characteristics and either R&D decisions or product market strategy. Some guidance, however, is provided by evolutionary theories. They conceive of firms as repositories

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[1] Less condensed histories are contained in a longer version of the paper presented at the conference on the evolution of firm capabilities at Dartmouth, September 1999. This version of the paper is available from the authors.

of competence that imply a pattern of specialization by entrants (Nelson, 1991).

If different types of expertise lead firms to enter an industry and subsequently produce different kinds of products and work on different problems, what kinds of expertise are important: Substantive expertise embodied in human and physical capital? Different styles of management learned from prior experience? And how precisely do expertise and the firms' (or their principals' in the case of *de novo* firms) prior experience influence and differentiate their perceptions about the future of semiconductor technology and products? Evolutionary theories, once again, focus on understanding firm competencies, and particularly the unique histories that generate them.

To be able to describe the nature and sources of firm differences, it is useful to understand, in the language of Nelson and Winter (1982), where the key knowledge resides within the firm that affects its operational and more forward-looking decisions. It is also important to understand how that knowledge is used. One possibility suggested throughout the management literature (e.g., Barney, 1994) and consistent with the conventional economic view of firms as unitary actors is that top management possesses this knowledge. What, however, is this key knowledge? Chandler (1962) underscores the importance of management in setting the strategic direction of the firm and internally allocating the firm's resources to achieve its goals. For managers responsible for units with multiple functions, it is also essential to know how to achieve cross-functional coordination and integration (Chandler, 1962; Iansiti, 1998).

Alternatively, the bureaucratic politics model conceives of firms as composed of individuals and groups distinguished by their goals, interests, and power, with key decisions the outcome of a bargaining process among different coalitions (cf. Allison, 1971; Barney, 1994: 64). Relatedly, in the principal–agent literature firms are thought of as nexuses of contracts mediating the interests of parties with different objectives and knowledge (Holmstrom and Tirole, 1989). Evolutionary theories of the firm offer yet a different perspective. These theories not only conceive of the role of top management as being limited, but view firms' choices as largely the outcome of historically determined routines (Nelson and Winter, 1982; Winter, 1988; Nelson, 1991). These different conceptions of decision making within the firm call into question the role of top management and whether decision making itself is deliberative or largely follows trajectories conditioned by past practice.

As semiconductor technology evolved and markets developed, firms had to make decisions about both their current and future products, processes, and capabilities. However these decisions were made, did perceptions of key decision-makers change over time to keep pace with changes in the industry? Did key managers recognize that at times their firms needed to change directions in significant ways? If so, were the firms constrained in making those changes and why? Did the firms understand the limits on their abilities to change? The answers to these questions are important if we are to understand how firm differences evolved in the industry. Among them, understanding the limitations on change is especially important.

One factor that can limit firms' ability to change is the inability to acquire key human and physical assets. The resource-based view of the firm stresses how tacitness can limit the marketability of key resources and also make them difficult to imitate. The ability of firms to change also depends on whether they can acquire and use extramural know-how and information. Related notions of absorptive capacity (Cohen and Levinthal, 1990), competency traps (Levitt and March, 1988), and core rigidities (Leonard-Barton, 1994) all suggest that the existing know-how of firms may constrain their ability to exploit new information and even recognize what information is worth exploiting (Cohen and Levinthal, 1994).

Another factor that may limit the ability of firms to change is ambiguous feedback from the environment. Some settings are sufficiently complex and uncertain that it is not possible even retrospectively to understand the basis for firm success (Rumelt *et al.*, 1994: 226). Competition may also limit the ability of firms to change. Ghemawat (1991) emphasizes the importance of commitments, suggesting that if firms delay pursuing key technological developments they can be preempted by rivals that have already captured the relevant market. Relatedly, Klepper (1996) and Sutton (1998) develop models in which R&D competition dictates a concentrated market structure, which suggests that firms may be foreclosed from pursuing a broad research agenda if they delay too long.

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If the past actions of firms distinguish their future efforts, can we think of these actions as coalescing in the form of capabilities? A key building block in the strategy literature is the concept of core capabilities; firms are presumed to be different and are advised to exploit their distinctive 'core' capabilities to succeed (e.g., Prahalad and Hamel, 1990; Andrews, 1971; Porter, 1980). This assumes core capabilities are hard to change and hence distinguish firms in an enduring way. If indeed firms can be usefully thought of as having capabilities that confer competitive advantage because they are hard to imitate, what are these capabilities composed of? Are they based on 'intangible' assets that involve tacit know-how and are difficult to imitate and purchase, as stressed in the resource-based view of the firm? Are the key capabilities of firms anything more than some specific know-how in a well-defined domain, or are they the ability to change over time, as stressed in Teece *et al.*'s (1997) dynamic capabilities theory? If Teece *et al.*'s argument is correct, then successful firms' key capabilities would be expected to change as the environment and technology evolve (cf. Fujimoto, 1999).

Finally, diversity among firms may have implications for social welfare as well as firm strategy. Rumelt *et al.* (1994: 44) crystallize this issue in the form of the following question: 'Is the search for rents based on resource heterogeneity contrary to public welfare, or does it act in the public's welfare?' The evolutionary literature (e.g., Nelson and Winter, 1982) and the literature on R&D spillovers (e.g., Griliches, 1991) suggest that social benefits could be realized in two reinforcing ways. Through the competitive struggle, only the 'best' performing technologies survive, and the greater the number of firms advancing the technology in different ways, the better will be the surviving best technology. Simply, the best technology selected is likely to be better the broader the field upon which the market can act (Nelson, 1982). Another way diversity can enhance technological progress is through complementarities that commonly exist in rivals' R&D activities (cf. Levin and Reiss, 1984; Cohen and Malerba, 1994). In such a setting, R&D spillovers can increase the productivity of each firm's R&D, making the 'best' surviving technology even better still. For spillovers to be realized, however, information has to flow across firms through various conduits, including the movement of engineering personnel, informal information exchanges, publication of firm R&D findings, and licensing. These conjectures raise a number of questions that in a technologically turbulent industry such as semiconductors are best applied to R&D and other technological activities. Did the firms conduct R&D on different problems, or when they worked on the same problems, did they pursue different approaches to solve them? To the extent that their R&D efforts differed, were the differences related to the firms' backgrounds and histories? Did the 'best' technologies survive, and were the best technologies improved by virtue of more actors working on different things? Did information channels exist that conveyed information about the R&D activities and findings of rivals, and did the productivity of the firms' R&D improve as a consequence?

We return to these questions after the histories of the four firms are related.

THE HISTORY OF SEMICONDUCTOR RESEARCH AND THE FIRM HISTORIES

In this section, we first provide background concerning the origins of the semiconductor industry. This provides a context for the firm histories which follow.

The semiconductor industry, as we know it today, traces its origins most clearly to the invention of the point-contact transistor at Bell Labs in late 1947 and the subsequent licensing of this invention and its immediate follow-on, the junction transistor, by Bell Labs beginning in 1951. Semiconductors had been objects of study—and much puzzlement—since the nineteenth century. The term refers to a class of materials that perform somewhere between an electrical conductor and an electrical insulator; hence the term, '*semi*-conductor.' Although many researchers sought fundamental understanding of this class of materials, such knowledge eluded them well into the twentieth century. Indeed, the commercial *application* of semiconductors preceded their fundamental understanding by a generation.

The advent of commercial radio in the early 1920s, emerging principally from the activities of amateurs, brought semiconductors into the world of commerce in the form of the crystal detector

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used in low-end radio receivers. These semiconductor crystals performed as a diode—an active circuit element that rectifies alternating current radio waves—thereby allowing them to be detected and heard through an earphone. Only with the emergence of quantum theory and its application to the solid state of matter in the late 1920s and early 1930s did researchers—including the very best physicists and physical chemists in the world—begin to understand semiconductor phenomena.

Radio's enormous growth during the interwar years, coupled with the burgeoning growth of long-distance telephony and other forms of telecommunications, made the development of a satisfactory semiconductor theory all the more important for the research community. The invention and development of the vacuum tube diode and vacuum tube triode in the first two decades of the twentieth century provided the basis for this spectacular growth. But vacuum tubes proved to be lacking owing to their burning out, their heat generation, and their limited electronic characteristics (signal gain, noise, and frequency range).

World War II provided the vital context in which intensive and wide-ranging semiconductor research and development would be done in the United States to address the shortcomings of vacuum tubes. Significant progress occurred through the coordinated efforts of the Office of Scientific Research and Development, involving university researchers and a number of industrial firms, including Western Electric, the manufacturing arm of AT&T and sibling of Bell Labs. At war's end, however, Bell Labs' research director Mervin Kelly, believing that semiconductor science and technology constituted an enormous frontier, organized a new fundamental research program in semiconductors for the postwar era. Led by physicist William Shockley, who had taught informal seminars on semiconductor theory at Bell Labs during the 1930s, the program involved a number of physicists, materials specialists, and electrical engineers. It soon led to significant advances in semiconductor theory (especially the role of holes, or minority carriers) and the invention of the point-contact transistor on December 23, 1947. Shockley subsequently invented the junction transistor, the patent for which was issued only days after the end of an important symposium in which Bell Labs began to transfer its research findings and inventions to would-be entrants in the new industry of semiconductor electronic device manufacture (Riordan and Hoddeson, 1997).

Because of its parent company AT&T's agreement with the U.S. Justice Department's Antitrust Division, Bell Labs offered licenses to any interested party willing to meet its up-front fee of $25,000 (for which credit would be given against future unit-based royalties). Its principal mechanism of technology transfer *vis-à-vis* the transistor was the quickly famous 'Transistor Technology Symposium' of 1951 and its sequel of 1952. By the end of the first 5-day symposium, licensees and the technical and procurement arms of the U.S. military services had gained access to a vast amount of formally *codified* knowledge about transistors, including their design, characteristics of operation, and the factors of design that influenced those characteristics and the basic materials from which they were constructed. In its 1952 symposium, AT&T conveyed information about the manufacturing techniques—many of them informal and depending on *tacit* knowledge—employed at Western Electric's point-contact transistor plant in Allentown, Pennsylvania. Owing to Shockley's invention of the superior junction transistor, however, many of those techniques were rapidly becoming obsolete.

With the exception of Fairchild, each of the firms considered in the present paper had representatives who attended the Bell transistor symposia. Each of these representatives, just as each of these firms, brought different sets of organizational capabilities to the manufacture of transistors and different experiences in the electronics industry. Their principals also held different views as to how important mastery of both the codified knowledge of semiconductor theory and the tacit knowledge inherent in transistor manufacture would be to their firms' success with the new technology. The histories of these firms are related in the order in which they entered into semiconductor production: Sprague first, followed by Motorola, Shockley, and Fairchild.

Sprague Electric

Sprague Electric, founded in 1928 by Robert C. (R. C.) Sprague, manufactured capacitors and other electronic components. The company supplied components to several important WW II

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research and development programs and emerged from the war enlarged and with an ongoing relationship with the military. The company's postwar research, mostly funded by the military, focused on printed circuits, ceramic-coated wires, and ceramic- and plastic-molded capacitors, which enhanced capabilities it acquired and strengthened during the war (Sprague Electric Annual Report, 1949). The military conveyed its enthusiasm for the transistor to defense contractors, Sprague included. Representatives from the firm were invited to attend both the 1951 military-sponsored Bell Laboratories transistor symposium, and the 1952 version for early transistor licensees. In the latter year Sprague also hired a new head scientist, Kurt Lehovec, to run the company's semiconductor research. Lehovec had worked at the Army Electronics Laboratory at Fort Monmouth, where he was an administrator of the 1949 Bell Labs/Joint Services transistor development contract. Lehovec began the company's foray into semiconductors by designing and building refining, crystal growing, and other process equipment (Lehovec, telephone conversation, 16 April 1995).

Impatient with R&D progress, in 1954 Sprague Electric licensed Philco's electrochemical transistor, which was manufactured using a highly mechanized production process. The Philco transistor was a natural fit for Sprague. Sprague's capacitor production employed electrochemical processes and Sprague had considerable experience making small electronic components and in the mechanization of production (Sprague Electric Annual Report, 1954: 10–11). The Philco manufacturing process chemically eroded a thin spot in the middle of a small piece of germanium and then electroplated it with indium to provide the transistor action. At the time, the Philco transistor was the highest-frequency transistor available. This characteristic suited military applications and computer makers, Sprague Electric's main customers, particularly well (Sprague Electric Annual Report, 1956: 12). Sprague built its ongoing development programs around the electrochemical device. In spite of reservations about the Philco device, Lehovec worked to improve the production process, especially in such areas as growing and refining germanium crystals (Lehovec, unpublished: 29–30).

By the mid-1950s Sprague's Research and Engineering Division included over 300 researchers. The great majority of them, however, focused on capacitor research, with the semiconductor efforts much smaller. In 1956 Sprague Electric hired an entire team from Philco to take charge of Sprague's new transistor plant in Concord, New Hampshire, which opened in 1957 (Sprague, 1993). The new plant introduced geographic distance between R&D and production, rendering their coordination difficult. R. C. Sprague, not adequately knowledgeable in semiconductor science, controlled the firm's research policy 'with a rigid hand,' frequently taking issue with the head of R&D, frustrating the company's development of adequate semiconductor-related expertise (Sprague, interview, 1 November 1994). He also headed the firm's 'Fourth Decade Committee' responsible for long-range research and development planning (Sprague, 1993: 75).

Under pressure from military demand for smaller, more reliable circuits, the company turned explicitly to problems of miniaturization (Sprague, interview, 1 November 1994; Kleiman, 1966: 31–68). Relying on its existing capabilities, Sprague produced two ceramic-substrate hybrid circuits. These used printed wiring and passive components with electrochemical transistors attached later. The company had long experience in producing the passive elements of such circuits; hybrids seemed a small step. In spite of late 1950s developments using silicon instead of germanium and photolithography rather than electrochemistry to make transistors, Sprague Electric stuck with its ceramic-based hybrid circuits until well into the 1960s, trying to capitalize on its historical expertise.

Kurt Lehovec, the company's chief scientist, worked on improving the electrochemical technology, proposing improved production techniques (Lehovec, unpublished: 29–30). Inspired by a 1958 conference where he heard a paper suggesting new complex circuit applications, he thought that such circuits could be made from conjoined transistors. Realizing that they would need to be electrically isolated from each other, Lehovec developed, and later patented, a method to do so (Lehovec, unpublished: 39). This patent (# 3,029,366, issued April 10, 1962), which outlined a method of using diodes to block current from flowing between adjacent transistors, later proved crucial to making monolithic integrated circuits.

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The shift in the industry to silicon-based devices coincided with the geographical shift of the semiconductor industry from the East Coast to Northern California. Sprague's location made it difficult to tap into the information networks beginning to spring up among the innovative firms in what is now known as Silicon Valley. The company's existing ties were with East Coast companies and universities—ties that Sprague's research manager later recalled 'provided precious little know-how' (Sprague, 1993: 70).

R. C.'s son, John Sprague, a Stanford Ph.D. in semiconductor physics, joined the family firm in the late 1950s. Rapidly assuming a prominent role in Sprague's research agenda, he focused the firm's efforts on gaining leading-edge semiconductor knowledge. The planar process, invented at Fairchild Semiconductor in 1958, was proving extremely useful in making transistors economically. John Sprague realized the importance of this new technique. His semiconductor team was small, six researchers to start, with the bulk of the firm's R&D focused on capacitors, the company's main business and one under attack by changing technologies and new competitors (Sprague, 1993). Sprague's planar R&D program struggled, hampered by its small size and the complex demands of the new technology. The early 1960s addition of the planar monolithic integrated circuit compounded the problem.

By 1963, Sprague Electric was the sole supplier of electrochemical transistors, a profitable position, but one that thwarted attempts to move away from the increasingly obsolete technology (Braun and MacDonald, 1982: 145). In 1962 R. C. Sprague, hoping for faster R&D progress, hired an entire team of researchers from Westinghouse, where they had been working on silicon planar devices. Though they were able to get planar devices into production in Concord, their presence and success exacerbated the rift between the R&D lab and production. John Sprague, seeking to eliminate this chasm, moved all semiconductor R&D to the firm's new Worcester, Massachusetts, plant (Sprague Electric Annual Report, 1968: 6). Many of the employees there promptly left, not wanting to work under an R&D person (Sprague, interview, 1 November 1994).

Though the firm produced transistors and later monolithic integrated circuits, it never gained significant market share. Losses plagued the firm from the late 1960s into the following decade. John Sprague increased its semiconductor R&D program throughout the 1960s, but the company's financial situation could not sustain the needed efforts. In the 1970s the firm was sold to conglomerates twice, finally dissolving in the mid-80s.

Motorola Incorporated

Paul Galvin founded the Galvin Manufacturing Corporation in 1928. The company first produced a battery eliminator for home radios, then complete radio sets, including the 'Motorola,' the first practical car radio. (Petrakis, 1991: 20–91). The 1930s brought relative prosperity to the firm. In the run-up to WW II, Galvin's engineers produced prototypes of the Walkie-Talkie, a crystal controlled two-way radio considerably smaller than existing Army units. Initially cautious, the Army ordered large numbers of the units after mid-1941 (Petrakis, 1991: 140–144). The company's reputation for building rugged equipment, first gained for its mobile radios, proved essential for the military market and strengthened the company's relationship with the armed forces after the war.

In the 1930s Galvin had hired Daniel Noble, an engineering professor and radio consultant, as the company's Director of Research (Noble, 1964: 6; Petrakis, 1991: 146). Noble was intelligent, opinionated, and highly driven to apply his learning. Galvin and Noble would remain the main influences on the company for several decades.

After the war Motorola (the name adopted in 1947) continued to serve the military and commercial radio and television markets. At that time the firm's main capabilities lay in printed circuits, ceramic substrates, and electronic system design and manufacture. Dan Noble, who gained exposure to the new semiconductor arts while representing Motorola at the MIT Radiation Laboratory and at Harvard's Radio Frequency Laboratory during the war, insisted that the company build a foundation in this new field (Noble, 1977: 18). In 1948 he chose Phoenix, Arizona, for a new research lab's location. Noble intended the lab to focus on military-sponsored research and to supply 'a window on the world of electronic research' (Noble, 1974: 1). At least two company representatives attended the 1951 Bell Labs Transistor symposium at the invitation of the military (AT&T Archives, 1951: 10). The firm apparently

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did not send anyone to the 1952 symposium, though by that time it had acquired a transistor license.

The semiconductor division's management was skilled in semiconductor science and technology. The R&D lab, which expanded from 40 staffers at its founding to over 800 five years later in 1954, focused not on new discoveries, but on taking 'new technology which was coming along somewhere else and … making it work' (Taylor, 1985: 30). Its main customer was Motorola's equipment divisions, and it focused on power devices, rectifiers in particular, for radios and other electronic equipment. This emphasis provided the technical background for the firm's later move into automotive electronics, which paid off hugely when the company developed the first practical rectifier for automobile use, allowing alternators to replace troublesome generators. To facilitate coordination between research and production, Galvin and Noble mandated close and constant communications between the semiconductor unit and the systems divisions. (Weisz, 1985: 17–18).

In the late 1950s the firm decided to expand into the commercial semiconductor market. Motorola had invested in a broad semiconductor R&D program to serve its internal needs; by the mid-1950s, though, the company's internal consumption alone could not support the Phoenix R&D efforts. Noble and Galvin further stressed that the company's expertise would only be an advantage if it entered the commercial field soon (Petrakis, 1991: 215–218). To stay current with customer demands the company broadened its research program further and hired individuals and teams of individuals from other companies including Western Electric, Hoffman Electric, and Bell Telephone Laboratories (DaCosta, n.d.: 36; Ackerman, n.d.: 9–10). By these means the Phoenix facility established a base of expertise in both diffused and alloy transistors. Motorola acquired a license from RCA for alloy transistors, a device suited to audio and power applications. Motorola also acquired scientific and technical information from other sources, particularly Bell Labs (Taylor, 1985: 30).

By the late 1950s enlarged production had weakened the coordination between R&D and production. To counter this trend, in 1958 Noble hired Les Hogan, a Harvard physics professor, as manager of the semiconductor division. Hogan broke up the existing organizational structure and replaced it with product groups with responsibility for both R&D and production (Taylor, 1985: 18). These changes 'tended to sacrifice even more the development of really novel and new technology' (Taylor, 1985: 37). He also maintained Motorola's wide-ranging R&D efforts that supported both the equipment divisions and other commercial customers.

Like Sprague and most other electronics companies, Motorola was greatly influenced by its work for the military. The emphasis on size and reliability compelled the company to address miniaturization. Dan Noble had long emphasized the usefulness of hybrid circuits because they took advantage of Motorola's existing areas of expertise and used proven components and production techniques (Noble, 1954: 4). Long experience with printed circuits, ceramic materials, and the design of rugged circuits made hybrids a good fit for Motorola. Further, hybrid technology's reliability, relatively low price, and suitability for both Motorola's internal needs and its main customers recommended it to Motorola management (Hogan, 1961: 3). By the end of the 1950s, however, responding to technological developments elsewhere and to continued military demand for small, complex circuits, Motorola semiconductor research included work on less conservative approaches to integration like thin film and monolithic devices and circuits (Motorola, Inc., 1960: 1).

Motorola struggled with monolithic integrated circuits, whose complexities demanded mastery of a wide range of interrelated production and testing technologies (Lesk, interview by M. H. Petrakis, 13 June 1989: 12). Like Sprague, Motorola was hampered by its geographic isolation from the new Northern California semiconductor center with its extensive channels of information exchange. This led the Semiconductor Division's research manager to bemoan the 'inbred' nature of the laboratory (Welty, 1989: 9). Further, Motorola's corporate research connections were with companies no longer on the technological frontier, such as RCA and Bell Labs (*Business Week*, 1962: 116; Golding, 1971: 51). These links could not provide the knowledge needed to move into monolithic integrated circuits, retarding Motorola's progress in that area.

The company's struggles with monolithic ICs did not prevent it from making important contri-

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butions to the development of those devices. In 1962, for example, the Air Force supported a $3 million project in Phoenix devoted to developing better techniques for producing thin films of metals and other materials, an area in which Motorola already had expertise from its extensive prior experience in printed circuits and in which it made lasting contributions to monolithic semiconductor technology (Miller, 1962: 85–95).

The company's investment in a broad research agenda, supported by the company's commercial, automotive, and military equipment divisions, and its ability to maintain that agenda over a long period of time, nonetheless enabled it to prosper eventually in the new technology. By the end of the 1960s Motorola had captured a significant portion of the IC market (Tilton, 1971: 69).[2] In the following decade it became a major force, becoming one of the largest manufacturers of computer chips in the world, a position it maintains today.

Shockley Semiconductor Laboratories

Shockley Semiconductor Laboratories was founded by William Shockley, one of the inventors of the transistor, and perhaps the pre-eminent semiconductor physicist of his day. Educated at Cal Tech and MIT, upon graduation in 1936 Shockley joined Bell Labs and became part of a new research group pursuing basic research in solid state physics (Hoddeson, 1977: 28). The war took Shockley away from Bell Labs. He worked on submarine warfare tactics, applying new operations research techniques, and consulted on radar training programs to optimize bombing accuracy (Baxter, 1946: 405–406). Shockley thus established a close relationship with the military which lasted throughout his subsequent career, including membership on the Department of Defense Research and Development Board and ongoing consulting relationships with all of the military branches.

Shockley played a mainly theoretical role in the 1947 invention of the transistor (Hoddeson, 1981: 68). Wanting to 'play a more significant personal role' in transistor development, Shockley almost immediately emerged with the ideas that yielded his most important patent, that for the junction transistor (Shockley, 1976: 599). Shockley also assumed an important role in the dissemination of semiconductor knowledge. His role in Bell Labs transistor symposia and his 1950 book *Electrons and Holes in Semiconductors*, which clarified the theory of transistor action, elevated him to the top of his field and provided him extensive and lasting contacts throughout the academic and industrial semiconductor community (Shockley, 1950); Hoddeson, 1977: 25–26). In 1955 Shockley took a leave of absence from Bell Labs for the purpose of 'investigating various opportunities' (Shockley, 1955).[3]

Shockley found backing for his venture from Arnold Beckman, founder of Beckman Instruments and a fellow Cal Tech graduate. Shockley moved into rented space in Palo Alto, California, and recruited employees for his company. His preeminence in solid state physics and broad and deep connections with the academic world allowed Shockley to secure the brightest young semiconductor scientists and engineers available, including some from his previous employer, Bell Labs. In 1956 the company employed 37 staff, 12 with Ph.D.s. Only four employees, however, were 'mechanical designers and production men' (Shockley, 1956). One year later, the research staff was 34 (Shockley, 1957a); 2 years after that, the production force was 20 and the research staff twice that, out of a total employment of just over 100 (Dimmick, 1959).

Shockley initially planned to make a double-diffused silicon transistor, a device invented at Bell Labs but which had not yielded to production. He could not, however, sustain this focus. Instead, he instituted a secret project on which a small number of his researchers worked (Moore, interview with D. Holbrook, 23 February 1994). Here for the first time in his commercial career Shockley's personal version of 'not invented here' syndrome emerges. His initial plan required the use of techniques developed by others; the secret project would be his conception alone and would repeat the scientific triumph of his junction transistor. In 1957 Shockley totally dropped the diffused silicon transistor, replacing

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[2] In 1967 Motorola's share of the IC market was estimated at 12 percent, roughly a third of Fairchild's, and half of TI's (Tilton, 1971: 66).

[3] According to a scientist who later worked for him, Shockley said that 'he had seen his name often enough in *Physical Review*; he now wanted to see it in the headlines of the *Wall Street Journal*' (Queisser, 1988: 82).

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it with efforts to develop a four-layer diode, a device of his own invention.

For the remainder of his tenure with the firm, Shockley promoted his four-layer diode. Almost immediately this emphasis drove away eight of his most talented employees to found their own firm, Fairchild Semiconductor. Initially attracted to Shockley by the prospect of working on the cutting edge of semiconductor technology, these men grew frustrated with the lack of emphasis on production. The 'traitorous eight,' as Shockley called them, included Robert Noyce and Gordon Moore, who later founded Intel. The prominence of the four-layer diode reflects Shockley's lack of emphasis on producing devices suited for the existing market. Shockley, primarily a theoretician, saw production as subsidiary to research. Theory, however, was no longer the most important aspect of semiconductor technology. Production required mechanical and engineering skills and a willingness to proceed without scientific understanding. Shockley's education and experience hindered his recognition of this fact. His choices of cooperative programs revealed this approach. His company would do the research while production would be farmed out.

Three years after founding the firm, Shockley summarized its position as still 'in a building-up stage' and 'consuming capital rather than making profits' (Shockley, 1958). Ignoring strong currents in the industry, Shockley's company made no efforts to produce miniature circuits, choosing instead to promote the four-layer diode as 'actually the first solid circuit produced in the electronic field' (Biesle, 1959). By 1960 the company still had no appreciable sales (Shockley, 1957b). Beckman, tired of the venture, sold the company to Clevite Corporation, an Ohio-based firm with existing interests in semiconductors. Shockley largely removed himself from the company, focusing on his new teaching position at Stanford University and consulting with the military services. In 1964 Clevite sold the firm to IT&T, which dissolved it in 1967.

Fairchild Semiconductor

The eight ex-Shockley researchers who founded Fairchild Semiconductor initially offered themselves as a team to a number of firms but then decided to form their own company. With financial backing from Fairchild Camera and Instrument Company, a New York-based firm, they set up shop in Mountain View, California, in 1957 (Malone, 1985; Braun and MacDonald, 1982: 72). Convinced that the silicon diffused transistor, a more stable device than the germanium transistor, would be warmly received in the market, the company's late 1950s activities were of two main types: designing and modifying processing equipment and mastering the intricacies of the required production processes. The technology demanded a diverse set of compatible and complementary skills that by chance and design collectively the eight largely possessed (Moore, interview with D. Holbrook, 23 February 1994; Malone, 1985: 90). At Shockley Semiconductor Labs the Fairchild eight had gained valuable technical skills and insight into silicon technology, as well as skills in designing and making various pieces of process equipment. They decided to pursue the double-diffused silicon mesa transistor (Moore, interview with D. Holbrook, 23 February 1994) and put the device into production a few months after founding the company.

The mesa transistor used a photolithographic production process that involved masking the silicon wafer surface with a layer of silicon oxide. Experimenting with this layer, Jean Hoerni, Fairchild's theoretician, invented the planar process in 1958. Instead of removing the oxide layer, Hoerni left it on the wafer surface, leaving the resulting transistors with a flat profile (hence the name) and giving them greater electrical stability. This process not only simplified production somewhat, but also produced more reliable transistors, and thus fostered mass production of transistors. Making planar transistors required the development of several interrelated sets of skills, including oxide masking and diffusion, mask making and photolithographic techniques, and metallization. Fairchild's research and development program for the following years aimed to tap the potential of the silicon/silicon oxide system.

Robert Noyce's invention of the monolithic integrated circuit in 1959 followed from Hoerni's planar process. Rather than cutting the wafer into individual transistors and then combining them into circuits, why not, Noyce reasoned, make multi-transistor circuits on a wafer (Noyce, 1977: 63–69; Wolff, 1976: 50–51). The oxide layer provided a surface for depositing fine metallic lines to connect the transistors into a circuit. Extending the planar process in this way made

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the monolithic IC practical, and provided the company with an early lead in what soon proved to be the dominant approach to integrating circuits. Fairchild's earlier success making and selling silicon transistors gave it the resources for the research needed to bring the IC to market.

By 1960 the company's R&D laboratory employed 400 researchers, the majority of whom were involved in developmental work rather than basic scientific research. The research laboratory was organized into functional areas, most of which focused on a specific part of the production process (Holbrook, 1999: 361–363). This close coordination of production and research brought problems to the fore, and allowed comparatively easy progress to be made in solving them. Gordon Moore and Victor Grinich, the directors of research and of engineering, gave researchers a great deal of autonomy.[4] The technical managers were all expert in semiconductor science and technology. By capitalizing on a diversity of technical and scientific opinions within the firm, Fairchild's management style allowed it to tackle and solve various technical problems with relative ease.

The company's research and development was guided by what Noyce called the theory of least knowledge (Moore, interview with D. Holbrook, 23 February 1994). When confronted with a problem, the first step was to take an educated guess at a solution. If it worked, no further research was needed. If it did not, then more research was performed and the next potential solution tried. Fairchild research placed little emphasis on basic research, eschewing scientific understanding in favor of pragmatic results. At times, of course, intractable problems demanded scientific understanding, and Fairchild made important contributions in some cases, but much of the knowledge generated at Fairchild was tacit, based on the specific experiences and exigencies of the company's production lines.

Between 1960 and 1966 Fairchild's increasingly powerful position in the industry and its growing reputation for superior research attracted attention throughout the industry, which in turn invoked two-way flows of information. Fairchild laboratory reports mention some 71 firms either supplying or receiving information during this period.[5] The expansion and prosperity of the semiconductor industry, however, also led employees to leave for greener pastures, 'spinning off' their own firms.

Expansion also eroded the close relationship between R&D and production. The company established production facilities away from its Northern California R&D labs for reasons of labor availability and costs, making it increasingly difficult to continue the close coordination of research and production (Moore, interview with D. Holbrook, 23 February 1994; Bassett, 1998: 230). Though Fairchild prospered in the first half of the 1960s and its research lab continued to produce leading-edge research results, the firm's production capability and new product output began to lag its competitors, and the firm lost market share. The problems discouraged Robert Noyce, who left Fairchild in 1967 with Gordon Moore and their colleague Andrew Grove to form Intel Corporation. Les Hogan from Motorola was hired to take over the firm. Though he enjoyed some success at Fairchild, the company was beset by new competition and new technologies in which it was behind (Malone, 1985: 124–127). Fairchild was sold to the French conglomerate Schlumberger in 1979 and again to National Semiconductor in 1986.

REFLECTIONS ON THE FIRM HISTORIES

In this section, we use the firm histories to reflect on the questions raised earlier. Our reflections are organized into six areas corresponding to the questions: entry, market segmentation and positioning, knowledge and decision making, limits on change, core capabilities, and diversity.

Entry and the sources of firm differences

Why did firms enter the emergent semiconductor industry? All four firms entered to exploit knowledge and connections developed from past activities. We consider in turn the motives for entry of Sprague, Motorola, Shockley, and Fairchild.

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[4] Moore, interview with D. Holbrook (23 February 1994): '[M]y inclination was to give the people that were doing [research] a fair amount of flexibility, thinking they knew best.'

[5] This was tallied from Fairchild Progress Reports between January 1, 1960, and November 1, 1966. SA 88-095.

An incumbent firm in the electronic components industry, Sprague saw dual opportunities in the manufacture of transistors. First, as a leading supplier of capacitors to the telecommunications and electronics industry, Sprague's executives expected that transistors would transform these industries, including the way they would use the firm's capacitors. Thus, the firm had to know something about transistors just to remain in business. But Sprague believed that its manufacturing know-how—ability to achieve high-volume production of reliable electronic circuit components—and its design knowledge—ability to design new and often proprietary circuit components—positioned it well to enter the transistor business. Doing so would not only buttress its existing product line, but it would also allow the company to exploit the close relationship the firm had developed with the military, which was both a major customer of its components and also a major funder of electronics R&D (especially in semiconductors). The military had chosen Sprague to be among the small number of firms to attend Bell Laboratories' first Transistor Technology Symposium; thus it had early access to Bell Labs' technology, and AT&T's consent decree assured that Sprague would have continued access to Bell Labs' deep knowledge of semiconductors, including product design and process know-how.

Motorola had a history similar to Sprague's in that it was an experienced firm in the electronics industry. It also had developed an important relationship with the military and was recognized by the services for its rugged telecommunications equipment. Thanks to its record, it was similarly well positioned to access Bell Labs' early discoveries. Like Sprague, it also had knowledge of nonmilitary electronics, but as a systems and end-product manufacturer, it had superior knowledge on this front.

Shockley entered the industry with four considerable assets. First, he possessed the reputation as the most knowledgeable theorist of semiconductors in the United States, if not the world. Second, he was the inventor of record of the junction transistor, which, employing his deep understanding of semiconductor phenomena, he had swiftly invented after his Bell Labs' colleagues Bardeen and Brattain had invented the point-contact transistor. Third, he had a close relationship with the military. This relationship had been fostered beginning in WW II when, using newly developed methods in operations research, he had helped to optimize strategic bombing programs. His interaction with the military had grown after the war when he became a member of the Research and Development Board of the Department of Defense. Indeed, he was regarded as an 'insider' by the military, and his fame as a transistor inventor made his connection with the military all the more valuable. Fourth, he was intimately connected with Bell Labs. Both he and his backers assumed that his access to Bell Labs gave him real advantages far beyond those of any Bell licensee. Yet, unlike Sprague and Motorola, he lacked the base of customers and the associated marketing and manufacturing experience of those firms. But he clearly believed that this deficiency was compensated by his prowess as a theoretical researcher, his reputation as an inventor, and his connections to the research community, which he exploited in recruiting an obviously top-flight staff.

Fairchild was the least well positioned of the four firms with respect to the market, but benefited from Shockley's astute judgment of talent and the experiences of its founders at Shockley Labs. The major (anti-)lesson they learned at Shockley was the necessity of keeping a sharp focus on getting a marketable product out the door. Fairchild's eight founders were a talented group with broad skills. While at Shockley, they also acquired valuable technical skills in the design and production of processing equipment and valuable insights into silicon technology which, once they left Shockley, enabled them to develop quickly a marketable transistor. So, although they did not have direct up-market experience, they possessed excellent scientific and technical knowledge and newly developed production skills, which positioned them extremely well for the emerging market.

To the degree that the distinctive experiences of the four firms conferred intangible assets, they support the resource-based view of the firm that firms enter new areas to exploit intangible assets initially developed for other purposes. Note that this conclusion holds both for the two pre-existing electronics producers and the two new firms, with the relevant experience for the new firms being the experience of their founders. Although the new firms did not themselves have organizational histories, their founders (e.g., Shockley and the

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staff he recruited) had histories from which they drew and which, to a large extent, helped to shape their respective paths.

Market segmentation and positioning

The initial products of the firms and the problems they worked on were directly related to their distinctive histories before entering the semiconductor industry. The key here is to understand what conditioned each firm's top managers' view or understanding of how to make money with semiconductors (i.e., what products to make for which markets) and what was necessary to get there (i.e., how to employ both human capital and equipment). These views were conditioned not only by their prior experience but also by their perceptions of scientific advance, technological change, and future uses of the technology.

Sprague believed that its manufacturing expertise would distinguish it in the semiconductor industry. Accordingly, it was content to license the technology it initially employed from Philco, which used a technology related to the technology Sprague used for capacitors and which yielded high-frequency transistors prized by the military both for their telecommunications applications and for use in computers. Motorola, reflecting its production of audio 'system' products and military products, limited its initial transistors to power devices suitable for radio and other communications equipment. This early emphasis on power devices further conditioned its subsequent application of semiconductors to automotive applications (i.e., rectifiers for alternators). Its heritage as an automotive radio producer and its experience in military applications of radios also conditioned it to focus semiconductor research on devices for its mobile communications equipment. Shockley concentrated on a device of his own invention, the four-layer diode, reflecting his confidence in his abilities as a theoretical physicist to develop important new devices, as he had done at Bell Labs. He was averse to mere imitation and to mere improvement of prior technology through small changes in configuration or manufacturing process improvement. He focused attention on inventing novel products, which led him to contract out development and production to other firms, matters he considered beneath his status. He specialized in research, which he perceived to be his comparative advantage. Novelty came at the expense of reduction to practice. On the basis of their experience at Shockley and their broad expertise, the founders of Fairchild focused initially on silicon transistors, which they were convinced would prove to be superior owing to their stability at higher temperatures. They also focused initially on the double-diffused mesa transistor on which they had worked at Shockley (and which he later abandoned), reflecting their commitment to developing devices that could be produced and marketed. Their commitment to silicon and to the mesa transistor conditioned their development of the planar process, which in turn, as Robert Noyce staunchly maintained, led them inevitably to the integrated circuit.

After their initial specializations, the evolution of the firms' portfolios of products and research problems continued to be influenced by the customers they served and their historical production expertise. Inevitably, firm behavior was also influenced by their successes and failures. Both Sprague and Motorola focused on discrete devices and hybrid circuits, reflecting the demands of their customers for discrete devices. Both firms produced discrete devices for radio and TV applications, and both firms produced circuits for computer makers, who initially favored reliable circuits of the hybrid type. Sprague's considerable expertise in ceramic circuits and its developing expertise in printed circuit boards led them to favor hybrid circuits. Motorola had long been pragmatically oriented toward producible devices and had developed great expertise in printed circuit technology, which favored the more conservative hybrid circuits in their efforts to miniaturize circuits. In both instances, specialization in hybrid circuits seemed to have slowed the efforts of both Sprague and Motorola to produce integrated circuits. Shockley remained committed over time to novel devices of his own invention given his theoretical orientation and egocentricity, both of which were reinforced by receipt of the Nobel Prize. Fairchild's focus on production and R&D serving production led it to focus on all aspects of production, which contrasted with Sprague and Motorola, both of which tended to acquire production personnel and equipment as well as to license technology for production from other firms. As its leaders came to understand more intimately the challenges of production and the opportunities available to the firm from a deeper understanding of its associated problems,

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the more this understanding conditioned their behavior in terms of the company's R&D program. They committed greater resources to process research while not abandoning work on product development.

Thus, the firms specialized according to their substantive technical knowledge and, for the two pre-existing firms, the types of customers they had serviced prior to semiconductors. No firm appears to have systematically scanned a wide range of possibilities and then made their choices based on a systematic comparison of the alternatives. Nor did any firm consider the actions of rivals with a view toward strategic preemption or matching in the marketplace. Rather, each followed an initial and subsequent course, acting almost instinctively to capitalize on their past experiences. Thus we find—at least tentatively—that the resource-based view of the firm seems to hold and that, upon finer-grain analysis, many of the conjectures from evolutionary theories of the firm seem to hold as well. In all cases, the 'strategic vision' of the firms' founders was limited by their past experience; these bounded visions tended to persist and to make a difference over a long period of time.

Knowledge and decision making

As stressed in a section above, differing states of knowledge about semiconductors, manufacturing, and markets help to explain firm decision making at the time of entry and conditioned subsequent firm performance. But knowledge continued to be a vital, if less-than-tangible, asset in firm behavior, especially as it conditioned executive-level decision making. The sources of knowledge, the flow of knowledge within the firms, and the locations within the firms where the truly 'key' knowledge resided appear to have been important to the long-run performance of all four firms.

The experiences of all four firms underscore the close coordination between R&D and production that was needed to make technological advances. In order for firms to improve their production capabilities, research was required on many different aspects of production, and in order to develop new devices firms had to develop new production skills, based in part on the production and application of new knowledge. This was perhaps most apparent in Fairchild. Its success stemmed largely from its ability to improve simultaneously multiple aspects of the production process. This ability rested squarely—at least in its heyday—on the ability of its key managers to produce new knowledge in their functional areas, to share that knowledge across functions, and, critically, to use that knowledge irrespective of where it was generated. Fairchild's two major technological breakthroughs, the planar process and the integrated circuit, grew out of its close coordination between R&D and production. The tensions palpable at Sprague and Motorola, where R&D and production were conducted in separate geographic locations, and the defection from Shockley of the eight founders of Fairchild due to Shockley's lack of emphasis on production in research and his frequent secretive research projects within his small organization, are matters of historical record. The differential performance of these firms clearly points to the interrelatedness of the knowledge generated in R&D and production as well as the need for close coordination between the two activities and sources of knowledge.

The ability of the firms to coordinate R&D and production was perhaps the most important determinant of their success over time. While top management was the final arbiter on all decisions involving the coordination of R&D and production in all four firms, the success of the firms in coordinating R&D and production was largely based on the structures top management set up to facilitate the coordination. Fairchild represented the extreme in which R&D efforts, in the firm's early years, were decentralized according to each functional area of production and in which R&D and production were carried out together in each area by teams responsible for both activities. This cross-functional coordination not only contributed to Fairchild's great early commercial success, but it also led to Fairchild's two major breakthroughs: the planar process and integrated circuits. When the firm grew large and geographically dispersed and when R&D had become highly centralized and an end in itself, this type of coordination broke down, contributing to Fairchild's decline—at least in two of the founders' minds. (Those founders, incidentally, left Fairchild to found Intel, where they deliberately banned any kind of research being done except on the factory floor.)

In Motorola, top management dictated frequent contacts and exchanges between production and R&D personnel located at different establish-

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ments. When this was not sufficient, Hogan was brought in to reorganize Motorola's efforts along the lines of (early) Fairchild in order to achieve closer coordination between R&D and production. Notably, Motorola was the only one of the four firms to survive and prosper for a prolonged period. Coordination of R&D and production at Sprague was carried out more via a top-down process in which a long-range planning committee, dominated by the firm's founder, R. C. Sprague, made the strategic decisions. R. C. Sprague's narrow orientation, reflecting his background in production and his relative ignorance of solid state physics, frequently led him to overrule the R&D director. Though it succeeded to some degree in the early transistor industry, Sprague was not able to adapt to developments brought on by the integrated circuit until it was too late.

Shockley was the ultimate in a top-down management style in which he resisted efforts by the eight defectors and his financier to focus the company's activities on production process rather than product innovation. Consequently, Shockley Labs never produced a commercially successful product in spite of the founder's definitive knowledge of semiconductor physics and his record as the inventor of the junction transistor.

Our four case histories, although not fully representative of the entire industry, underscore the critical role of top management in identifying what knowledge was critical for firm success, creating structures in which that knowledge could be secured, and then coordinating the flow of that knowledge across functions. Thus, one of the key points for understanding differences across the firms is not simply where the key operational knowledge resided within the firm, but where top management believed it to reside and how they tried to combine it.

The importance of cross-functional integration is consistent with Chandler's (1962) view of the role of top management in industrial firms and is subsequently highlighted by Iansiti (1998) in his examination of product development in the computer industry. Chandler emphasizes the importance of top managers in coordinating the different functional areas of corporations. This coordinating role that we observe as being critical in semiconductors is different from both the nexus-of-contracts view of the firm in economics and the bounded role of management in evolutionary theories. The need for coordination between R&D and production resonates with the emphasis in the nexus-of-contracts view of the firm as involving different units, each with their own knowledge and interests. However, the importance of top management in achieving effective coordination attests to the inability of purely contractual specifications to limit the tensions between R&D and other functions and to channel those tensions into creative activity bounded by pragmatism. Moreover, that this role was performed so differently and effectively in the different firms suggests it involved not only managerial discretion but also great skill.

The role of top management in coordinating R&D and production is also different from top management's role in setting broad strategic parameters for decision-makers as emphasized in the evolutionary view of the firm. In the semiconductor industry, however, the knowledge intensity of product design and process control meant that to be effective in setting strategic direction top managers had to possess this knowledge and then act on it. Fairchild is the best example here. In the case of Motorola, however, top management recognized its own limitations but compensated by deftly involving more knowledgeable personnel in R&D, manufacturing, and marketing in charting the strategic direction of the company. In Motorola's case, cross-functional coordination could also generate effective strategy.

Limits on change

The semiconductor industry changed markedly in the period covered by our firm histories. How did the key decision-makers perceive changes in the industry as they occurred? In turn, did they perceive the need for their firms to change, and given these perceptions, how precisely did they formulate such needs? When they formulated a strategy of change, were they constrained in carrying out this strategy? Our four histories offer a remarkable spectrum of phenomena *vis-à-vis* change over time. The pattern for each is reasonably clear, but of course we are working from imperfect information in all four cases so our observations are tentative.

With the exception of Shockley Labs, which never progressed very far, leaders in the firms recognized changes in the industry and attempted to change considerably over time. Both Sprague and Motorola sought to broaden the types of semiconductor devices they produced. In Sprague this occurred when John Sprague entered the firm. Motorola recognized early on the need to broaden its technology to justify its broad-based R&D effort in semiconductors, which it felt was necessary to keep up with advances. Both firms also attempted to master integrated circuit technology when the advantages of monolithic circuits over their hybrid approaches became apparent. Fairchild was one of the two leaders in silicon semiconductor devices, but, late in our period, when it fell on hard times, Fairchild's leaders attempted to change by bringing in Hogan from Motorola to right itself. The record indicates, though, that all three firms had difficulty changing. With the exception of evolutionary economics, the various theories discussed earlier allow firm leaders to recognize that change is necessary, but they offer markedly different views on constraints on change.

Change largely involved keeping up with a rapidly moving technological frontier. Much technological knowledge is tacit, and it has been conjectured in the resource-based view of the firm that such knowledge is difficult to acquire in the market, making it difficult to keep up with rapid technological advance. The record on this score is mixed. Up to the era of integrated circuits, Sprague, Motorola, and Shockley all were able to purchase information that was largely tacit; all three firms were able to hire individuals and even teams of individuals with important technological knowledge from Bell Labs, RCA, GE, and other firms. They were also able to hire key people from academia. They also acquired equipment and technology licenses from similar firms. For a while, this enabled them to stay abreast of technological developments in the industry.

But the invention and development of integrated circuits brought about changed conditions in the industry. As the pioneer of the integrated circuit, Fairchild sensed little need for change. Indeed, from the time of their defection from Shockley, Fairchild's founders sensed that they were on the right path of semiconductor development. Their approach to technological change was to do more of what they were doing and to figure out how to do it better. The development of the mesa transistor and the planar process at Fairchild quickened their arrival at the next major milestone in the industry, necessitating no fundamental change within their organization or their approach to the technology and the industry. Rather, Fairchild forced change on its competitors.

Both Sprague and Motorola tried to master integrated circuit technology, and both encountered formidable problems. The record is brief but suggests that both Sprague and Motorola found that producing an integrated circuit required far more tacit knowledge than had been required with prior technological advances. Furthermore, there were many interrelated technological advances involved in integrating circuits, all of which had to be mastered. Although perhaps some of the requisite knowledge could be purchased in disembodied or embodied form, it appears that much could not, and without complete mastery of all the interrelated aspects of integrated circuit technology, the firms had difficulty.

Another reason for the greater difficulties Sprague, Motorola, and Shockley encountered in changing over time was that their sources of information were becoming increasingly obsolete. All but Fairchild were connected to Bell Labs, RCA, and other eastern electronics firms that increasingly were not at the technological frontier of the industry. After about 1953 or 1954, Bell Labs was no longer at the technological frontier owing to its comparatively limited application of semiconductors in the Bell system, especially *vis-à-vis* miniaturization. Continued reliance on Bell and other eastern firms attenuated the knowledge Sprague, Motorola, and Shockley received about technical and market-related developments, which appears to have handicapped them. Had they been better connected to firms at the technological frontier, perhaps they would have been able to purchase the tacit knowledge they needed to keep up with developments in integrated circuits.

Despite its acknowledged difficulties, Motorola was eventually able to master integrated circuit technology and prosper, whereas Sprague was not (Shockley did not try). A definitive explanation for these outcomes is impossible, but the record is suggestive. One possible explanation is that Motorola committed early to a broad R&D program, whereas by the time Sprague realized the importance of such a commitment it was too late. For example, at the time that John Sprague joined the firm, the firm had done little research on many of the basic processes fundamental to monolithic chip production (specifically Sprague had done little on diffusion, mesa transistors, and planar technology). Although Sprague did increase its R&D expenditures substantially in the integrated circuit era, it never seemed to generate enough sales to yield sufficient profits to cover its R&D expenditures. In contrast, early on Motorola recognized the need for a sufficiently large sales base to be able to support the broad-based R&D it thought necessary to keep up with technical advances. It chose to produce a much wider range of semiconductor devices than required to service its own needs and to market its full line aggressively. This strategy provided considerable profits and resources to support R&D in areas that proved to be critical in the manufacture of integrated circuits. Fairchild, of course, committed early to a very broad R&D program that was key to its success. Thus, early commitments may have played an important role in the success of Fairchild and ultimately Motorola and in limiting the ability of Sprague to change.

Neither Fairchild nor Motorola, though, appear to have made their commitments to preempt rivals. Fairchild's broad R&D program was driven by its emphasis on mastering production problems and arriving at consistency of product and process—factors that account for both its initial and continued successes. As Robert Noyce later argued, Fairchild's early commitment set it on a trajectory that led to the integrated circuit. This trajectory was so fecund and the firm's commitment was so extensive that Fairchild later could not change course (away from the bipolar elements of their integrated circuits and toward the MOS design); hence Noyce, Moore, and Grove found it easier to leave Fairchild and establish Intel than to change Fairchild. Motorola's strategy for change was aimed internally, not for any preemptive purposes; it sought to rationalize its own R&D efforts, which required a larger sales base than its own needs could generate. The importance of having sufficient sales to justify a large R&D program is consistent with the models of Klepper (1996), Cohen and Klepper (1996), and Sutton (1998). In these models, firms need to have a large enough output over which to apply their innovations in order to generate sufficient profits to cover the costs of their R&D. This imperative limits the number of firms that ultimately can survive and maintain a broad R&D program, making early commitment particularly important for long-term survival.

Core capabilities

If a firm's entry and continued profitability in an industry are conditioned by such intangibles as know-how, access to scientific and engineering networks, and other forms of tacit knowledge, can we think of these things joining with the past actions of firms to constitute something called 'core capabilities'? Our histories speak, at least modestly, to this question. Each of the firms had intangible assets, in the form of distinctive expertise and connections, which they exploited in choosing their products and the problems on which they worked. The histories suggest that these intangible assets were beneficial but were not generally sufficient to provide enduring profits. Sprague, for example, was able to use its prior experiences initially to earn substantial profits in semiconductors, but eventually its intangible assets proved to limit its ability to adapt. Fairchild's initial intangible assets also proved initially to be extraordinarily valuable, but as the firm grew its top management's efforts to coordinate R&D and production faded and Fairchild declined. Only Motorola was able to sustain its success. Thus, consistent with the dynamic capabilities theory, the most important capabilities are ones that enable a firm to adapt to technological and market change over time, and only Motorola appears to have possessed these capabilities.

What explains Motorola's 'dynamic capabilities' (Teece *et al.*, 1997) or 'evolutionary learning capability' (Fujimoto, 1999)? The history of Motorola speaks only softly to this question and sometimes with mixed messages. We offer two of them here in an attempt to identify the key factors that shape the dynamic capabilities of firms. One message centers on the skill of managers in coordinating R&D, production, and marketing. Motorola's managers appear to have been quick to observe changes in the environment and were willing to change their firm's course when it was deemed necessary to survive in such a changed environment. We have already underscored the importance of Motorola's size and scope in helping to make such change possible. Yet another message, not necessarily contradictory to the first, and consistent with an important role for preexisting knowledge and experience in affecting expectations (Cohen and Levinthal, 1994), is that Motorola's strong position and technological leadership in the upstream market for semiconductors—mobile telecommunications, consumer electronics, etc.—put it in an excellent position to monitor, forecast, and adapt to change in the market for semiconductors. Other firms in the industry, of course, were fully comparable to Motorola in this respect. Our histories do not encompass those firms, however, and thus our reflections on dynamic capabilities remain limited at best.

Diversity

The four semiconductor firms we examined developed and produced different sets of products and employed different manufacturing methods. They also often conducted R&D on different facets of semiconductor technology, and, even when their R&D efforts were dedicated to the same goals, they often adopted different approaches. While the four firms surely differentiated themselves to reap profit, the record suggests that the differences across these firms also accelerated the pace of technological change in the semiconductor industry and, in the process, yielded social benefits.

Different forms of diversity confer different kinds of social benefits. At the most obvious level is the diversity that stems from firms specializing in different products for buyers with different needs and tastes. Clearly, the more options that can be offered to such buyers, the greater their overall welfare. Diversity can even be beneficial when firms produce competing variants of the same product. Even if only one is ultimately selected, the more variants the better the expected quality of the winner. But, in many instances, there is also a borrowing of features from the losers which improve further the selected winner. Similar arguments apply to R&D. When firms work on competing approaches to solving the same technical problem, it is reasonable to conjecture that the more approaches explored, the better the quality of the outcome (Nelson, 1982). When firms work on different problems, advancing distinct facets of a technology, they can build upon one another's findings as long as the requisite information flows across firms, yielding complementarities that accelerate the pace of technical advance (Holbrook, 1995).

The kind of diversity associated with firm specialization was evident from the outset of the semiconductor industry. The four firms began by producing different products based on different materials and production methods that serviced different types of customers. Upon entry Sprague pursued germanium transistors, worked on improving production processes such as materials refining and crystal growing, and, on the basis of Philco's patent, developed high-frequency transistors for computer makers. Motorola entered with the objective of manufacturing silicon devices and soon arrived at the design of new products for a broad range of applications, including power rectifiers for the automotive and other industries and transistors for audio applications and mobile communications. Though Motorola also contributed to production process development, its most significant contribution in the early phase of the industry was in widening the scope of silicon transistors in the market. Fairchild's founders made the production of practical silicon devices its highest priority and devoted their principal efforts to reducing uncertainty and variability in every step of the manufacturing process. Pursuing this strategy led to their focus on the mesa transistor and the invention of the planar process, which when pushed to this approach's ultimate logic led to the monolithic idea—the integrated circuit. Shockley directed all his organization's efforts to the development of novel devices in which he could claim authorship.

The firms not only specialized but also competed, both by producing variants of the same product and attempting to address the same technical challenges in different ways in their R&D, largely reflecting their distinctive skills and expertise. Although this type of diversity did not address different customer needs and eventually was winnowed out through competition, it nonetheless also seems to have contributed to social welfare. In some cases, the firms developed complementary innovations, which collectively contributed to greater advance than any one firm alone was capable of achieving. We suspect as well that by having multiple firms work on the same problem it also raised the chances of any particular type of advance being realized. Consider, for example, one of the most important advances achieved in the early years of the industry, the miniaturization of circuits.

The impetus to miniaturize electronic circuits came from the armed services. Each branch thought reductions in size and energy consumption were imperative to advancing its weapons

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systems and thus increasing national security, a major concern throughout the Cold War. To the degree that firms in the incipient semiconductor industry targeted military markets for their products and derived R&D funds via contracts from the military services, miniaturization modulated their strategy and firm behavior, at least in part. But not all firms solely targeted military markets. This alone ensured diversity of approaches to miniaturization. Moreover, even the firms that worked for the military tended to pursue different approaches to miniaturization, reflecting that each service ran its own miniaturization program and each service's R&D program managers hedged their bets by pursuing a range of approaches to miniaturization. Thus, in spite of the pursuit of a common objective, diversity was the order of the day.

Conditioned as they were to military markets, both Motorola and Sprague pursued hybrid circuit R&D, which involved mounting discrete transistors on ceramic substrates on which printed circuits and passive components had been deposited. This approach exploited both firms' existing skills in materials and processes, but the two firms pursued very different approaches to the realization of hybrid circuits, owing especially to their very different 'initial conditions' at the time of entry in the semiconductor industry. Motorola possessed far greater upstream knowledge of circuits given that it was the dominant manufacturer of mobile communications equipment. It approached miniaturized hybrid circuits from a very pragmatic position, reflecting a realistic assessment of its capabilities and its R&D leader's philosophy ('Our motto has been *Profit* first, then progress of the revolutionary kind.'). Consequently, its initial approach was to incorporate discrete transistors, which it had begun to make, into standardized modules based on printed circuits (a technology that Motorola had mastered in high-volume production). But Motorola's experience with its equipment in the field also led it to put a premium on ruggedness in its circuits, thus conditioning how it approached component protection, insertion, and soldering in printed circuit boards. Hedging its bets, Motorola also simultaneously pursued a less conservative miniaturization research program in thin film circuits, which sought to deposit both passive and active circuit elements on a substrate in thin layers. Like Motorola, Sprague pursued the conservative technology of hybrid circuits owing to its experience as a passive circuit element supplier to the military. This experience conditioned its leaders to think of electronic circuits as collections of distinct elements that were assembled into a whole rather than as something whose elements could be integrated. It placed far less emphasis on ruggedness, and it did not pursue as aggressively the building-block approach inherent in Motorola's pursuit of modularity.

Shockley exhibited no interest whatsoever in miniaturization.[6] Certainly Shockley was aware of military wants and needs. He had been, after all, a member of the Pentagon's Research and Development Board, and once he decided to establish his own company, he traded heavily on his connections to military R&D organizations. But catering to the military did not provide Shockley with enough room to pursue the kinds of novel innovations that he perceived as his comparative advantage and that would satisfy his ego.

Fairchild's 'traitorous eight,' as the history shows quite clearly, sought to get a product out the door as soon as possible, a product that would exhibit consistency of performance characteristics, something that its principal customer (initially the military services) also valued. Fairchild focused on transistor manufacture, especially mastery of processes that determined quality, reliability, and uniformity of product. When pushed to its logical extreme, the company's invention of the planar process of making silicon diffused mesa transistors led one of its founders, Robert Noyce, to ask why so much time was devoted to cutting transistors out of a silicon slab and then packing them individually only for them to be laboriously soldered into circuits when they could be simply wired together with other photolithographically deposited circuit elements (e.g., resistors and

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[6] Perhaps this reflected a kind of mindset that pervaded his former employer, Bell Laboratories. Although Bell Labs responded to the needs of the military in many different ways, its leaders demonstrated little interest in what later became known as integration. They seem to have been content with discrete circuit components which could be substituted for vacuum tubes in their vast telephone switching network. In making this substitution of transistors for vacuum tubes, Bell Labs and its AT&T cousin Western Electric put a premium on reliability and performance rather than on saving space and energy; the Bell system had already amortized its vast telephone exchanges and repeater stations, and it had incorporated energy costs into its rate base.

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capacitors) to achieve an integrated circuit. Without its internal development of great skill and know-how in diffusion methods (whose lineage goes back through Shockley Laboratories to Bell Labs) and especially in oxide masking techniques, Fairchild could not have succeeded in realizing the idea of the integrated circuit.

Although not explicitly discussed in the firm histories, Texas Instrument's efforts in the nascent semiconductor industry suggest some additional observations about the role of diversity. TI is universally credited with the production of the first silicon junction transistor, which it first publicly demonstrated in May 1954. The key to TI's success in this endeavor stemmed in large measure from the work of Gordon Teal, a former Bell Labs researcher whose ideas about producing pure, single-crystal semiconductor materials were rejected for a long time within Bell Labs (including by the leader of Bell Labs' semiconductor research program, William Shockley). Thus constraints imposed by Bell Labs' managers became opportunities for differentiation at TI. Given that TI's major market strategy was to meet military demand, its semiconductor research program was also heavily influenced by the services' goal of miniaturization. This objective manifested in TI's recruitment of Jack Kilby from a small electronics firm located in Milwaukee, where he had worked on hybrid circuits. He was assigned specifically to work on the miniaturization problem; disenchanted with hybrids, his solution was the integrated circuit. Kilby realized in practice his ideas for integration before Noyce did at Fairchild, although, following a long, bruising patent fight, the two are almost universally regarded as co-inventors of the integrated circuit. Noyce and Fairchild were in a far better position to manufacture integrated circuits with superior methods because of Fairchild's earlier development of and commitment to the mesa transistor and the planar process.[7]

The two firms' routes to the integrated circuit differed significantly. These differences mattered and even conditioned the two firms' behavior after their respective patent documents became known to each other, owing both to the initial conditions that prevailed at the time of the firms' entry and to their different paths pursued following entry. For example, the two firms approached the packaging of their integrated circuits in fundamentally different ways, stemming in part from differences in the fabrication of the chips themselves. Though the two firms arrived at, loosely speaking, the same spot, their trajectories carried them in different directions very soon after their brush with one another.

The achievement of miniaturization via the integrated circuit suggests how diversity characterized by competing approaches to the same goal can contribute to technical advance. The history of miniaturization also illustrates how diversity contributed to technical advance by making available different but complementary—rather than competing—technologies. This was clearly observed in the unintended contribution to the integrated circuit made by Sprague and Motorola, which ironically grew out of their failed attempts to achieve miniaturization through hybrid circuit development. Most notably, Sprague's Kurt Lehovec's patent covering diode isolation of conjoined transistors was critical to successful integration of active elements on a semiconductor monolith. Every firm making monolithic ICs used Lehovec's patent, which Sprague widely licensed. It was, however, the product of Lehovec's individual talents as an inventor and researcher rather than the result of specific organizational expertise at Sprague. Motorola's substantial experience with printed circuit technology definitely fed back into the industry's drive toward the monolithic approach in that it had mastered the photodeposition of thin metallic layers on substrates. These techniques were vital in connecting the circuit elements laid down on a single slab of silicon.

Thus, firms such as Fairchild and TI that devoted their miniaturization efforts to monolithic circuits contributed different kinds of innovations, and others such as Sprague and Motorola that worked on other approaches were also able to contribute to the monolithic approach. Diverse approaches to semiconductor product design outside the miniaturization project similarly fueled a number of other technological advances in the industry that fed back into the monolithic approach. Most notable among these approaches is the MOS (metal-oxide-silicon) transistor, which gave the industry the 'gate' that is now funda-

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[7] As Noyce later said, 'We were in a position at Fairchild where we had, because of the particular way we had decided to make transistors by leaving an oxide layer on top of them, one more element than everybody else did to build into the package to make the integrated circuit, and that happened to be the one that worked' (Braun and MacDonald, 1982: 89).

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mental to the microprocessor (Bassett, 1998). As one research manager at Bell Labs commented on his organization's huge giveaway of the transistor and the formalized knowledge that lay behind it, the opportunities for semiconductor electronics were far, far greater than Bell Labs and the Bell system could reasonably fully exploit. Diversity ensured that much of the opportunity space presented by the transistor's invention was both fully explored and aggressively exploited.

While the different backgrounds of the firms led them to make different choices, which appear to have enhanced social welfare in a number of ways, it is important to recognize how various features of the environment supported or even nurtured their diversity. One key feature of the environment supporting the industry's diversity was uncertainty regarding the most fruitful directions for advancing product and process technology. The environment was also characterized by a rapid evolution and differentiation of user needs as well as uncertainty regarding those needs and associated applications. Government also played a direct role in supporting the semiconductor industry's diversity, particularly through procurement policies that represented a series of different and sometimes competing bets on everything ranging from the most fundamental features of the technology to specific applications.

Key features of the environment also enabled those differences to contribute to social welfare. It almost goes without saying that a system of for-profit market capitalism that selects superior products, processes and, in turn, firms, was key to the realization of the impact of diversity on technical advance. Furthermore, the technical advances achieved in the semiconductor industry from the joining of the knowledge emerging from different firms' R&D efforts could only be realized in an environment supporting a relatively unencumbered flow of information across firms. The miniaturization project, for example, was characterized by enormous information flows across firms and suppliers. Military R&D program officers often played critical roles in spreading information, seeking as they did to make the most of their hedged bets. Licensing, publications, and professional society conferences devoted to miniaturization also insured the flow of information about the varied approaches to miniaturization. More generally, antitrust and intellectual property policies that encouraged the liberal licensing of technology (illustrated most saliently by AT&T's liberal licensing of the fundamental transistor technology) were also essential to the rich flow of information. Intellectual property policy also did not impede knowledge outflows that resulted from the formation of spin-offs and the mobility of personnel.[8] Indeed, Fairchild itself epitomized the importance of an easy flow of information to the realization of the benefits of diversity. The firm's contributions clearly depended on the ability of frustrated employees with a different vision from their employer's to start their own firm and subsequently develop innovative products and manufacturing methods that greatly enhanced social welfare.

IMPLICATIONS FOR STRATEGY AND POLICY

The foregoing case studies, although clearly limited, suggest important differences across firms. Two broad differences appear to have mattered, particularly for the performance of individual firms and, to a more limited extent, for the industry as a whole. First, firms differed considerably in their technological goals. Even when different firms' goals corresponded, they pursued those goals in significantly different ways. These differences appear clearly in the R&D activities of the firms, and they accrued over time. Second—and important for individual firm performance but perhaps less significant for the industry—firms differed in the ability of their top managers to integrate the activities and information flows across the different functional areas of R&D, manufacturing, and sales.

The cases suggest that the sources of these differences stemmed from the pre-entry and early post-entry experiences of the firms (i.e., Motorola and Sprague) or their principals (i.e., at Shockley and Fairchild). These experiences had lasting effects on both what firms perceived to be worth

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[8] Mowery and Nelson (1999: 380) support this point when they state, 'In semiconductors, a combination of historical accident and U.S. government policy resulted in a relatively weak intellectual property rights environment for most of the first three decades of the U.S. industry's development. This environment was conducive to high levels of cross-licensing and entry by new firms, which contributed to rapid growth and innovation.'

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doing and on their ability to do it. They included each firm's prior development and application of specific technologies; their established and often geographically proximate networks of information from rivals, other firms (e.g., AT&T), and buyers (including government); and their leaders' or founders' management practices and related perceptions of the knowledge required to succeed and how that knowledge should be marshaled.

The effects of these experiences endured during the period we examined not because the firms did not see the need for change, but because, when a need for change was recognized, as in the case of Sprague, they found change difficult. Constraints on change stemmed in part from an inability to secure the necessary kind of expertise and to integrate it across functions sufficiently rapidly to remain at the technological frontier. This is especially evident in the drive toward miniaturization that blossomed in the invention of the integrated circuit. Motorola stands as the singular case of successful change. That success probably stemmed from its technological and financial ability and willingness to place a broad range of early bets in the form of a diverse range of R&D activities, as well as from its knowledge of prospective applications that came from its upstream integration into end-user markets. Motorola gained the expertise to move quickly as the market for integrated circuits took off; its internal demand and strong links to government buyers allowed it to dedicate sufficient resources to achieve its objectives and also to update dynamically its bets on the technology's future applications.

We are struck in these cases by the relative absence of the sort of decision-making process, commonly assumed by economists, that would lead firms to converge rapidly to some similar set of R&D and production activities. The firms we studied seldom, if ever, deliberated over a range of technological and business options and then selected a particular path. Even when they were somewhat deliberative, they were typically too constrained by past events and existing capabilities to depart substantially from past practice. In our firms' decision making, we see relatively little attention dedicated to monitoring—no less matching or preempting—competitors. The firms were too focused on their own challenges to look up. Thus, the nature of their decision making limited convergence in their R&D and production.

Although a study of four firms in a single industry considerably limits what can be inferred for business strategy and public policy, the experience of Sprague, Motorola, Shockley, and Fairchild and the semiconductor industry provide some narrow basis for informed speculation. Our study suggests that differences across the four firms affected their individual performance and survival. For example, Shockley's belief that a strong patent position was key to success, and his associated inattention to the market and production, seemed to have doomed him. Sprague's late embrace of integrated circuit technology and weak links to key information sources as the technology evolved undermined its long-run viability. Fairchild, in contrast, arrived on the scene with the right configuration of technical expertise and management practices. This happy combination of scientific and technical knowledge, engineering skills, and organizational instincts about the need for cross-functional integration yielded early dramatic success—at least for a short period. As both its manufacturing and research organizations built their own distinctive capabilities and cultures, Fairchild gradually lost its distinctive ability to integrate manufacturing and R&D. The firm also lacked the ability to retain key personnel as the external demand for their individual capabilities lured them away. Motorola's deep experience in government and private sector applications of the electronics technology positioned it well.

To say that firm differences mattered, and even arrive at some coarse understanding of what firms in this industry needed to know or have in order to succeed does not, however, yield clear prescriptions for strategy and business policy. Our analysis is necessarily *ex post*; we know things that top management did not and could not readily discern *ex ante* due to the enormous uncertainties and complexity that surrounded the rapidly evolving technology of semiconductors, their applications, and the nature and strength of final demand. Given *ex ante* uncertainty, one would then be tempted to believe in the wisdom of Motorola's nurturing of what we might now call 'dynamic capabilities,' that is, the ability to learn and change. Even that prescription is too glib and benefits unduly from our knowledge of how things turned out. Motorola put those pieces in place largely because it already spanned a broad range of functional areas, and possessed strong

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links across R&D, manufacturing, and the end-product markets. So, a bit like Fairchild early on, its ability to succeed was at least partly conditioned by what it brought to the party, that is, what it was doing prior to the emergence of the semiconductor industry; in other words, luck mattered.

In light of *ex ante* uncertainty, perhaps the only prescriptions one can make are that firms should both try to understand where an industry is going and develop an objective understanding of their own capabilities as well as the constraints on changing those capabilities. But this prescription is rather too facile as well if one accepts the possibility that it is actually difficult to do any of those things, even to understand the firm's own capabilities. If top management could do these things, though, it is not even clear that the firm should exploit its core competencies or try to change them. The best course of action may be to recognize limits and act accordingly. Arguably, this is one way to interpret what Noyce, Moore, and Grove did when they left Fairchild to form Intel, and what Intel did subsequently when it exited from the memory chip market decades later (cf. Burgelman, 1994). Indeed, Sprague and Shockley's benefactor, Beckman, would have likely profited from early exits.

Although mainly nihilistic implications for business strategy emerge from our limited study, its implications for public policy are a bit more constructive. It appears that, at least in the formative stage of a technologically turbulent and advancing industry, the industry as a whole benefited from the differences that existed across firms, particularly differences in their R&D activities. We have highlighted how differences in *ex ante* and early post-entry experiences of firms and their principals conditioned these differences in R&D activities. Rivalry among the technical units of the various service branches of the U.S. military and the different needs of other customers in the market for electronic components also played roles in creating diversity in technological approaches and capabilities. Via licensing and less formal channels, Motorola, for example, benefited from the early efforts of Sprague. Fairchild of course benefited from the spillover of technical know-how from Shockley, and all the firms of course benefited from the work of Shockley and his colleagues while they were at Bell Labs. More generally, the dominant technology of integrated circuits that eventually emerged embodied the findings of the broad range of firms that worked on miniaturization—beyond the four that we examined, including firms that survived as well as those that exited. In the early semiconductor industry, the existence of multiple firms distinguished by their capabilities and orientations enhanced the rate of technical advance of the industry as a whole.

This one case would suggest that, at least in the case of emergent or technologically active industries, government should consider adopting policies that foster diversity. Examples of such might include antitrust policies that protect entry, subsidies to startups, or support of university or government research that might directly spawn or support a broad range of diverse R&D activity within an industry. In the case of the semiconductor industry, policies such as the forced licensing of AT&T's transistor technology and multiple military service pursuit of miniaturization, as well as tolerance for employee mobility across competitors, had this effect. More generally, there is no reason to believe that, in the absence of these policies, the rate of technical advance achieved in the semiconductor industry would have been as great.

ACKNOWLEDGEMENTS

We thank the U.S. Small Business Administration for financial support.

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