A Role-Based Ecology of Technological Change[1]

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This article considers what factors determine whether an innovation becomes a foundation for future technological developments rather than a "dead end." The authors introduce the concept of the technological niche, which includes a focal innovation, the innovations on which the focal innovation builds, the innovations that build upon the focal innovation, and the technological ties among the innovations within the niche. Using patents and patent citations to measure characteristics of innovation niches within the semiconductor industry, the authors show that the size of the niche and the status of the actors within the niche have a positive effect on the likelihood that subsequent innovations will build upon the focal innovation. Competitive intensity within the niche has a negative effect on this likelihood.

I. INTRODUCTION

The power of technology to mold the arrangement of social activity has long been a topic of sociological interest (Marx 1954; Schumpeter 1950). This concern is manifest in the substantial literature on technology's influence on formal organizational structure (Woodward 1958, 1965; Thompson and Bates 1957; Perrow 1967), informal relations within organizations (Barley 1990), and the survival prospects of individual or groups of organizations (Tushman and Anderson 1986; Barnett and Carroll 1987). The role of technology in shaping population-level outcomes and in structuring organizations has been an intellectually active, central area of inquiry in the sociology-based research on organization-

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environment relations. However, while great effort has been devoted to the formulation of general propositions regarding technology's ability to configure social relations, there is much less systematic understanding of the dynamic process according to which particular technologies become advanced and extended, while others are never developed. Sociologists have conducted numerous, detailed historical studies that document the direct or diffuse competitions among alternative technologies (Hughes 1983; Law and Callon 1988), but there is a distinct absence of "middle range" sociological theory (see Merton 1968) regarding the determinants of technical change.

Consider any technological domain, such as microelectronics or biotechnology. To the extent that the actors that develop those technological areas devote their energies to one particular pursuit, they will in general be unable to devote those same energies to other undertakings. In effect, ideas and innovations compete with one another for the allocation of resources and attention. Some technological solutions will become "winners" in this competition, drawing the interest and effort of those actors involved in the development of the technological domain. These winners are likely to become a foundation for the future advancement of technological knowledge. Others will be "losers" in this competition in the sense that they will become technological dead ends. While the distinction between winner and loser should be regarded as end points on a continuum rather than as a dichotomy, this distinction helps to frame the central question that this article will consider: What are the factors that determine the degree to which a technology succeeds in this competition for resources and thus becomes a foundation for future technological developments?

If technically superior innovations were always to dominate technically inferior ones, then the answer to this question would depend upon the technical attributes that make a particular innovation superior. However, it is frequently observed that the "best" technologies (e.g., on the basis of price-to-performance ratios) are not necessarily the most successful ones, and this means that technical specifications alone may not be sufficient to gauge the likelihood of technological success (Katz and Shapiro 1984; Farrell and Saloner 1985; Arthur 1988). Because of the uncertainty surrounding the technical promise of an innovation, we argue that an innovation's ultimate contribution to technical advance is not simply contingent on its inherent technical properties, but to a large degree on its "niche."

While we formally define the technological niche of an innovation below, we can anticipate our framework with the observation that most innovations do not emerge in isolation. Rather, they build upon preexisting innovations and may themselves become foundations for future innovations. Thus, a given innovation is embedded in a relational context that can be defined by its connections to other innovations. Our framework uses the connections among innovations to bound a focal innovation's technological niche. Loosely, we can now state the theoretical claims of this article. We argue that the historical importance of an innovation is largely determined by three attributes of its niche: (1) the extent to which a focal innovation is proximate enough in technical content to the expertise of other innovators that these other innovators are likely to build upon the focal innovation; (2) the competitive intensity, or degree of differentiation, among the innovations to which the focal innovation is linked; and (3) the identities of the actors associated with the focal innovation and the innovations to which the focal innovation is connected. Patents and patent citations, which represent, respectively, innovations and the technological commonalities that indicate technological ancestry, provide the data for an empirical assessment of these claims.

Our article is organized as follows. Section II briefly reviews some of the literature on technical change. Section III develops in greater detail the theoretical underpinnings of the technological niche and also specifies the hypotheses that we test. Section IV describes our data. Section V discusses our study's empirical setting—the semiconductor industry—and our sample—all U.S. semiconductor device patents issued between 1976 and 1991. Section VI presents our measures and our modeling strategy, including the specification of the statistical equations that we estimate. The final two sections present our results and then offer a discussion and conclusion.

II. TECHNICAL CHANGE IN SOCIOLOGY AND EVOLUTIONARY ECONOMICS

Sociologists and organization theorists have long recognized the importance of technology in affecting organizational and industry-level outcomes, but scholars working in this area have typically been agnostic about the underlying determinants of technical change. To date the sociology-motivated, empirical research on technical change has too often ignored the factors responsible for the genesis of the technologies under study. Thus, in research on technology's influence on social structure, the analyses generally take place after the focal technologies have been developed. Even work that attempts to understand how organizational variables affect whether an invention gains a significant market presence assumes the prior existence of the invention (e.g., Stinchcombe 1990).

One exception to this agnosticism regarding the determinants of technical change is the emerging literature on the sociology of technology, which extends the social constructivist perspective that has been advanced in the sociology of science (Latour 1987). Through "thick description" of technological controversies and their resolution, the social constructivists emphasize the rich connections among actors and their innovations in technological arenas. These scholars use the network image of a "seamless web" to describe the dense pattern of relations concatenating the innovations and associated actors in unfolding technological systems. Regarding technological progress, a central insight of this view is that the development of new technologies occurs through an inherently uncertain process: There is no archetypal way to accomplish a particular technological endeavor, and therefore there may be many suitable alternatives that satisfy the demands of the technological task at hand (Hughes 1987). This perspective highlights the subjectivity of technological developments; it flatly rejects the notion that technologies are deterministic or that superior innovations necessarily dominate inferior ones (Pinch and Bijker 1987).

Despite the social constructivists' important theoretical contribution, however, a review of this literature raises three concerns. First, it is surprising the degree to which the work in this tradition has proceeded independently of sociological work on organizations and markets (see Tushman and Nelson 1990; Green 1992). This is a concern because the overwhelming majority of innovative activity takes place within the organizational context of what are often industrial firms. Second, the studies in this tradition tend to be retrospective, considering successful technologies and offering ex post explanations for their success (Staudenmaier 1985). This methodology causes much of the research in the sociology of technology to suffer from a strong selectivity bias. Third, the use of "network" in this literature has been more metaphorical than rigorous, and, perhaps in part due to the lack of explicit measurement and in part owing to this tradition's preference for thick description, this research has yet to yield generalizable propositions concerning the rate and direction of technical change.

The absence of general, sociological propositions regarding the rate and direction of technical change is noticeable when compared to economic work on this topic. A particularly distinctive aspect of many economic analyses of technical change is the degree to which they might be regarded as sociological in character; many of the assumptions that sociologists find objectionable in mainstream economic theories are significantly relaxed in explorations of technology. For example, the evolutionary approach to the study of technical change (e.g., Nelson and Winter 1982; Dosi 1984) builds upon a conception of the firm developed by behavioral organizational theorists such as Cyert and March. In these models, boundedly rational, "satisficing" (searching for acceptable rather than optimal solutions) organizations follow standard operating procedures in pursuing research and development. This process leads to a highly path-dependent search for new technologies. The consensus in this literature is that technical change is a gradual process, characterized by the accumulation of minor improvements to incumbent technologies.

As implied by terms such as "technological paradigm" and "technological trajectory," evolutionary theorists contend that technologies develop along paths that are determined by technical properties, as well as problem-solving heuristics and the skills and knowledge contained in a paradigm (Dosi and Orsenigo 1988). Therefore, a simplistic interpretation of evolutionary economic theories of the rate and direction of incremental technical change proposes that these are determined by properties of the technology itself or that they can be inferred from the local search practices of organizations. In these theories, bounded rationality plays a critical role: At the organization level its manifestation is local search, and at the individual level it is apparent in uncertainty about future technological directions. However, such theories lack what we consider to be the defining element of a sociological perspective: a sensitivity to the relational context in which the advancement of technological knowledge takes place.

In the next section, we introduce the concept of a "technological niche" as an analytical construct that focuses directly on the relational context that coevolves with technical change. As the social constructivist perspective does, we highlight the relationships among the actors involved in developing particular technologies. We do so by mapping the technological linkages among innovations that are developed by different actors, and we use the structure and composition of this mapping at one point in time to formulate hypotheses about how it will look in the next period. We rely on patents and patent citations to construct these mappings or to document unfolding technological paths. This approach forgoes some of the thick description that characterizes the work of the social constructivists for a conceptual framework and empirical approach that yields generalizable and falsifiable propositions about the process of technical change.

III. THE TECHNOLOGICAL NICHE

We define the technological niche at the level of the individual innovation. Using the social constructivist's conception of technical change as an unfolding network as our point of departure, we label a focal innovation's location in this network as that innovation's niche. Each niche consists of nodes, which represent innovations, and ties, which signify the common threads of knowledge that flow from one node to the next as time passes. In our analysis, each innovation occupies an egocentric niche that includes (1) the focal innovation, (2) the innovations on which the focal

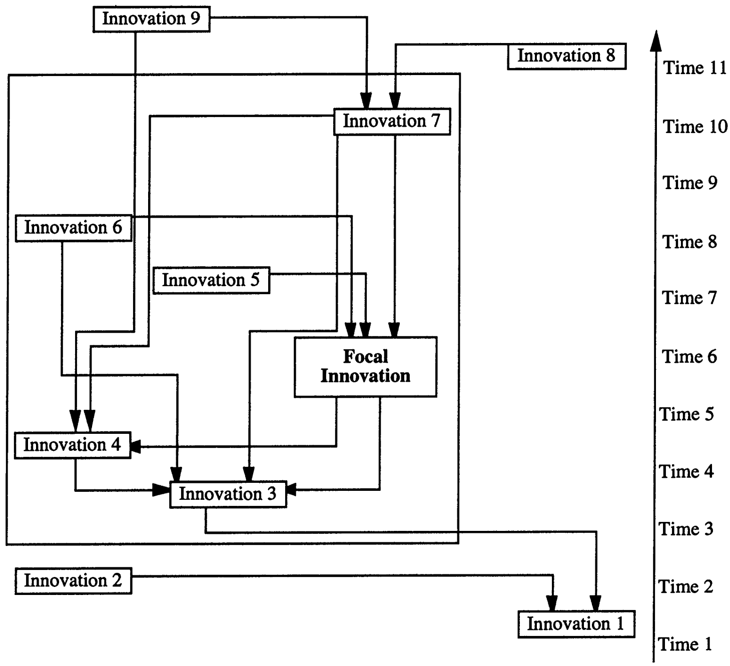

FIG. 1.—Technological niche, defined to include only those innovations to which the focal innovation is directly tied. The box demarcates the boundary of the niche. Arrows indicate patent citations; they point in the direction of the earlier time period, indicating that later innovations build upon earlier ones.

innovation builds, (3) the innovations that build on the focal innovation, (4) the innovations that are sufficiently close to the focal innovation in content that they help to circumscribe the focal innovation's technological contribution, and (5) the technological ties linking these innovations.

Figure 1 provides an example of such a niche. The egocentric niche includes all of the innovations in the box and the technological ties between those innovations. We use the term "tie" to denote technological commonalities among innovations. An innovation A has a tie to B if the contribution of A incorporates, builds on, or is bounded by a technological contribution of B.[2]

[2] Such technological ties between innovations can be regarded as a subset of knowledge-based ties between actors. The broader category of knowledge-based ties would include not only the linkages among innovations but also social ties among actors. Because the actors in our analysis are organizations, examples of knowledge-based ties would include such formal interorganizational alliances as patent cross-license agreements, and technology exchanges. Informal knowledge-based ties would include such connections as personal relationships among technical personnel employed by different organizations.

This egocentric conception of the niche is similar to the conception of the niche as role or relationally defined position (White 1981; Burt 1992; Podolny 1993, 1994; McPherson 1983; DiMaggio 1986). Given this role-based definition, the full technological network can be conceptualized as an interlocking role structure, and each new innovation represents both the emergence of a new niche in that structure and an entrant into one or more established niches. Accordingly, one could analyze technical change either as a process of niche emergence or niche entry. In our view, there is greater analytical leverage to be gained from the latter formulation. We adopt this approach because, if one were to frame the analysis of technical change as a process of niche emergence, it would be unclear where one would look for the causal mechanisms underlying the advancement of technological knowledge. In framing technical change in terms of niche entry, however, the search for the determinants of technical progress turns naturally to an examination of the niche itself, and the central question becomes: How do the characteristics of the niche affect the likelihood of a new entrant?

For our purposes, there are three primary ways to characterize the structure and the composition of the technological niche. One is in terms of the innovations themselves, with purely technical features representing the important distinguishing criteria. The second is in terms of the identity of the actors that own the innovations in a niche. As the social constructivist perspective highlights, underlying every technological network is a community of actors involved in its elaboration. For applied technologies, this community is likely to include business firms with products that incorporate the technologies, as well as universities, government-sponsored research labs, and research consortia that together supply essential technological knowledge to manufacturing firms. The distribution of these actors across the technological network provides a criterion in addition to the technological attributes of innovations to distinguish between niches. The third way to categorize different niches is in terms of niche structure. By structure, we refer to the number and the pattern of relations that connect the innovations in a niche.

Like capital-rich entrepreneurs who might enter one of many organizational niches, innovators may perceive numerous niches into which they might enter.[3] But given fixed resources and perhaps well-established

[3] The question of niche entry can be posed as, Which regions of the technological network should the organization enter? or as, Which product areas should the firm pursue? While there is clearly a strong correspondence between the two, we focus on the technological niche, because nonmarket organizations (i.e., universities and research institutes) play an important role in technological development and because technological development can proceed without influencing markets.

competencies, these actors cannot pursue every possible avenue for future innovation; instead they must adjudicate between niches, deciding to enter only those with the greatest perceived promise. Certain innovations will prove to be central to the advance of technological knowledge and thus of great economic or at least prestige benefit to the organizations that own them. However, others in the same technical arena will remain peripheral to this technological advance. Clearly, the decision to invest resources in a particular niche is one of large consequence to the actor. We now shift our attention to consider how the three attributes of the niche that we have identified are likely to affect the process of technical change.

The Quality of the Focal Innovation

If the promise of an innovation were an easily observable feature, then the decision of which niche to enter would be a relatively simple one. However, it is striking the degree to which inherent technical properties fail to serve as reliable guides for discerning the innovations that become most successful. For example, when Intel Corporation developed the microprocessor, one of the landmark inventions in the semiconductor industry, the company was unaware of its significance. According to Gilder's (1989) account of the microprocessor's development, at the time of the innovation Intel's sales staff believed that the company would never sell more than 10,000 microprocessors, and the firm's board of directors expressed concern that the chip would distract Intel from focusing on its principal markets.

The observation that technical characteristics alone cannot sufficiently inform decisions about which technologies to develop is a claim that is not unique to academics; it is also made by participants and close observers in different technological domains. For example, a 1993 article in *Electronic Business,* an electronics trade publication, focused on the recent flurry of interest in flash memory, a technology that was important for the inchoate market for personal digital assistants (handheld computers). Flash memory allowed a computer to write and quickly erase information from semiconductors that retained data even after their power supply had been cut. The author writes, "Remember bubble memory? How about Josephson Junction? The chip industry is littered with products and technologies that were the subject of huge amounts of hype but never panned out. Despite these cautionary tales, the drum beats are growing even louder for . . . flash memory. Although flash seems likely to escape the disastrous fates of these earlier technologies, some healthy skepticism seems warranted" (Ristelhueber 1993, p. 99).

We note that pervasive uncertainty is not limited to the development of specific new product areas. It is often the case that technological debates surround even well-established, basic technologies. For example, a long-standing controversy in the semiconductor industry has pitched silicon against gallium arsenide (GaAs) as the choice material upon which to engrave microscopic circuits (i.e., as the basic material for building integrated circuits). This debate has persisted because silicon has certain properties that make it easier to pack a large number of circuits on a single chip, but GaAs circuits are faster at equal or lower power than silicon circuits. Furthermore, GaAs has properties that make it appealing for building optoelectronic semiconductors (devices that detect, amplify, or transmit light). Still, silicon chips have dominated the history of the industry to date, but for many years some industry participants have foreseen a larger role for GaAs chips. As the former head of IBM's Advanced Gallium Arsenide Technology Laboratory noted, many advocates of silicon referred to GaAs as "the technology of the future, always has been, always will be" (Brodsky 1990, p. 68).

Each of these examples points to a situation in which technical uncertainty surrounded a new innovation, technical controversy, or more generally, a high-technology pursuit. It is precisely because of the uncertainty surrounding predictions of the potential of innovations that the second characteristic of niche composition, the identity of the actors that own the innovation in the niche, becomes important to consider.

Attributes of Niche Occupants

We argue that under conditions of technological uncertainty, the status of the actors that sponsor the innovations in a technological niche serves as a tangible guide for the probability that the focal innovation in that niche will become important. We define an innovator's technological status as the perceived quality or importance of that actor's previous contributions to the advancement of technological knowledge. The more that an actor's previous innovations are perceived to have served as the foundation for successful innovational paths, the higher is that actor's status.

In the above quotation on the significance of flash memories, the author expressed skepticism regarding the future promise of this innovation. What is left unexplained, however, is why the "drumbeats are growing even louder" for this technology rather than for the others that the author noted (Josephson Junction and bubble memory). One possible explanation is that the inventor of flash memory technology in 1986 was Toshiba and the leading promoter of this technology was Intel Corporation. Toshiba and Intel are among the most successful and innovative firms in the semiconductor industry. We argue that the combined status of

Toshiba and Intel provided an indication of the likelihood that flash memory would become an important technology.

Anecdotal evidence that a prominent organization or individual actor can bolster expectations for a product by virtue of its association with that product is prevalent. For example, IBM's entry into the personal computer market in 1981 provided the impetus for software developers to devote substantial resources to programs designed for the personal computer (Anders 1981). This example illustrates how the actions of high-status organizations can become "focal points" (see Schelling 1960) for the allocation of resources by the broader array of actors within or around a particular domain.

The general observation that an actor's status affects the attention that the actor receives from the larger community is supported by research in the sociology of science (for a discussion of the connection between the sociologies of technology and science, see Pinch and Bijker [1987]). Merton (1968) observed how scientists' identities provide a biased lens through which the quality of their intellectual contributions are evaluated. He labeled this phenomenon the "Matthew Effect." Given that the contribution of a scientist's work cannot be assessed until a sufficient amount of time has elapsed for others to develop its implications, a work at its introduction is more readily taken to be important or innovative if it is produced by a high-status member of the scientific community. As a result, the likelihood that a work of a given quality will become the foundation for future research is greater if its author is of higher than lower status.

Sociological research on markets has emphasized a similar status-based dynamic. Specifically, Podolny (1993) argued that a status hierarchy among producers in a market induces a flow of resources that causes a variation in quality across producers' products consistent with, and thus confirming, the initial status ordering. Though Podolny (1993) formulated his argument with respect to the attention and resource allocation processes of consumers, we believe that the argument can easily be extended to the attention and resource allocation processes of innovators.[4] If actors working in a technological area expect that a technology will be superior, they will devote more resources to that technology than to alternatives that are evaluated to be inferior. Consequently, the technologies sponsored by high-status actors are more likely to be rapidly developed than are competing ones, and they will thus appear as superior ex post despite the fact that they may not have been superior ex ante. For example, if

[4] An interesting empirical question is To what degree is an organization's status in the market related to its status among other innovators? Unfortunately, our data do not allow us to make this assessment.

the combined status of Toshiba and Intel leads others to devote resources to the development of flash memory rather than to competing technologies, such as ferroelectronics, then this additional flow of resources will increase the likelihood that the high expectations for flash memory, as well as the superior status of Toshiba and Intel, will be confirmed.

The fact that an actor's status is expected to lead others to favorably evaluate its innovations does not imply that a high-status actor's innovations will always, or even regularly, be of greater historical significance than those of a low-status actor's innovations. It implies only that on average there will be an ex post positive correlation between an actor's status and the acknowledged importance of that actor's innovations. Perhaps of greater importance, the conception of status as an attribution that is contingent on an actor's previous contributions to technological knowledge does not imply that the causal connection between contribution and status is from the former to the latter. To the extent that an actor's status beckons others to enter a particular innovation's niche and thus increases the likelihood that others build upon its innovations, status by definition increases the contribution of an innovation. To draw on another of Merton's expressions, the Matthew Effect may hold in part because status engenders a "self-fulfilling prophecy" with respect to the contribution of an innovation.

In terms of the niche framework, we contend that actors rely on the status of the inventors of focal innovations to inform their decisions about which niches are most likely to become the foundation for superior technologies. These considerations lead to our first hypothesis:

HYPOTHESIS 1.—*The greater the status of the actor associated with the focal innovation, the greater the likelihood of a new entrant into the niche at a point in time.*

In addition, we expect that the status of the other actors in the niche will influence the perception of the promise of the focal innovation. To the extent that others use an actor's status to evaluate the importance of the actor's innovation, the actor's status indirectly serves as evidence of the quality of all innovations with which it shares a technological tie. Because we define niches as egocentric networks that comprise clusters of innovations linked by technological ties, we suspect that the status of all of the actors owning the innovations in a niche signals the importance of the central innovation. In effect, when high-status actors publicly acknowledge the importance of an innovation, they draw to it the attention of the other members of the technological community. Accordingly, our second hypothesis states:

HYPOTHESIS 2.—*The greater the status of the actors associated with* *the nonfocal innovations in a niche, the greater the likelihood of a new entrant into that niche at a point in time.*

The discussion of status illustrates certain positive externalities that exist across technological ties. Each innovation (and corresponding actor) helps to legitimate other innovations that possess a similar technological content (and their owners). However, as Schumpeter (1950) highlighted, the process of technical change is in large part a process of competition. Technological ties are a source of legitimation, but also of competition, since they imply a technological commonality among innovations. Accordingly, we suggest that an important factor shaping both the willingness and ability of a would-be innovator to enter a niche is revealed by the structure of that niche.

Attributes of Niche Structure

We argue that the relational structure of the niche indicates the intensity of competition within that niche. While competitive intensity is not a directly observable feature of a niche, ecologists (Hawley 1950) have long drawn on Durkheim's (1933) important insight that there is an inverse relationship between differentiation and competitive intensity. More recently, Hannan and Freeman (1989) have emphasized the importance of segregating processes in reducing the competitive intensity in the niche. For our purposes, a crucial analytical question is How can differentiation be measured in a technological niche? Were there some analogue to physical or resource space, then it might be possible to simply count the number of innovations that surround a focal innovation in that space. However, we find implausible the assumption that there is a fixed carrying capacity for a type of knowledge that is independent of the realized level of that knowledge. In the domain of technological knowledge, there is no clear analogue to physical or resource space. Therefore, we rely upon the indirect ties in the egocentric network (i.e., the ties among the innovations to which the focal innovation is connected) to reveal the level of differentiation in the technological niche.

Consider, for example, an innovation that draws on diverse strands of knowledge and then becomes the technological ancestor of a highly differentiated array of innovations. That innovation's egocentric network could be represented as in figure 2. The underlying differentiation is evidenced by the absence of technological connections among the innovations to which the focal innovation is tied. The laser is perhaps an example of such an innovation, because it has spawned multifarious innovations in unrelated domains, such as consumer electronics, medicine, and telecommunications. The fact that the nonfocal innovations do not share

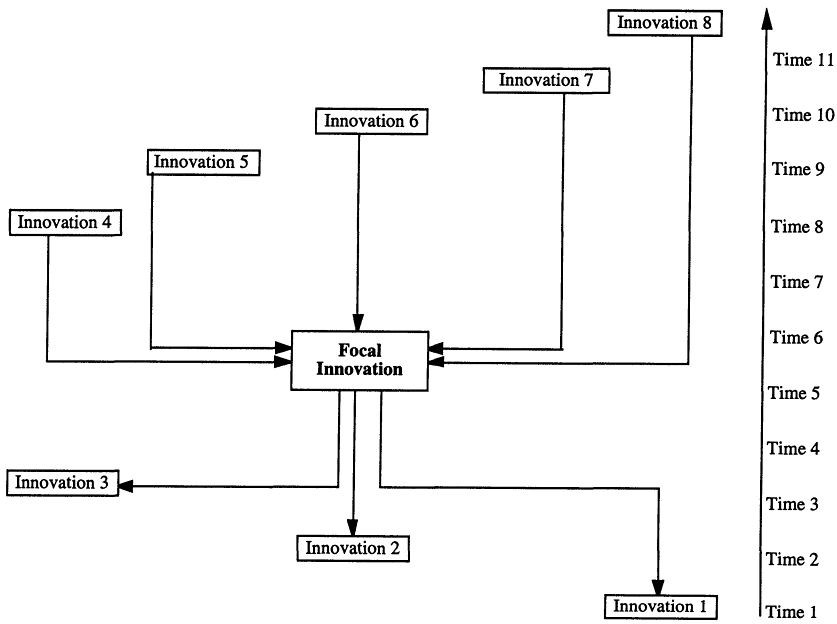

FIG. 2.—Hypothetical sparse niche. The arrows point in the direction of the earlier innovations, indicating that innovations developed later build on earlier ones. The absence of indirect ties among the nonfocal innovations suggests that the figure represents a differentiated niche.

technological ties implies considerable differentiation of technological knowledge in the niche. Conversely, consider the network around an innovation that draws on interconnected innovations and that spawns innovations that are themselves only slightly differentiated. An example of such an innovation, drawn from our own data on the semiconductor industry, is represented in figure 3.

The number of direct ties provides no information about the level of differentiation in the technological content of the innovations within a niche. The central nodes in figures 2 and 3 are both directly connected to an equal number of innovations, and, while the direct ties are relevant to the signaling processes to which we just alluded, it is the indirect ties that provide information about differentiation and hence competitive intensity. The more indirect ties that surround a focal innovation, the more the network can be seen as folding in on itself, blanketing the focal innovation.

The use of indirect ties to measure differentiation can be easily derived from network theory. According to both Granovetter (1974) and Burt

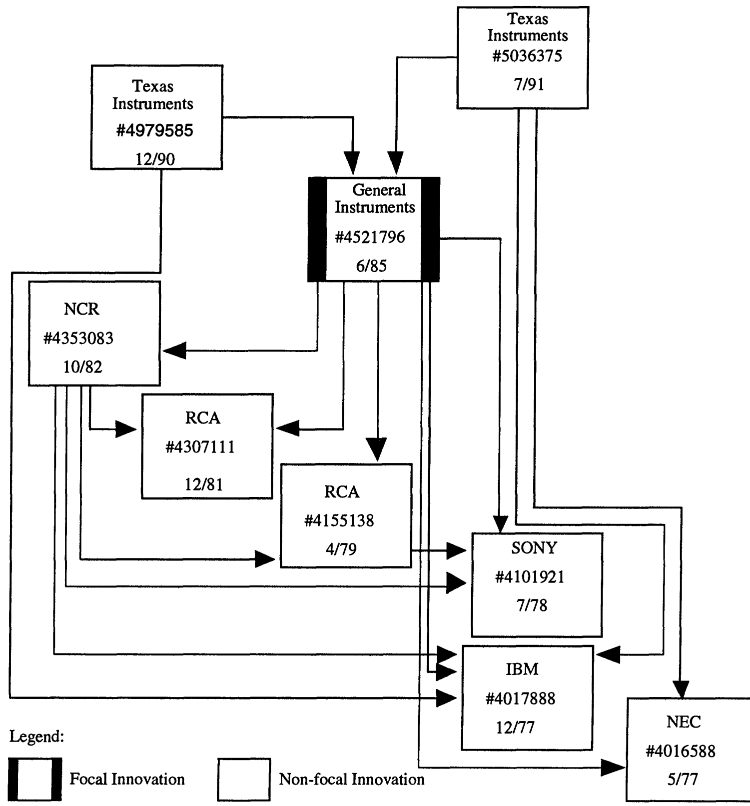

FIG. 3.—Niche of patent no. 4521796. Each box represents a patent and provides information on the patent's owner and issue date. Arrows represent citations from one patent to another. The presence of numerous indirect ties among the nonfocal innovations suggests that there is low differentiation within the niche.

(1992), the information that an actor receives from two alternative contacts is redundant to the degree to which those two actors are connected. More generally, the more connections there are among the nodes within the egocentric network, the less differentiated is the informational content at each node. Thus, the greater the density of technological ties in a technological niche, the more the innovations can be considered to be technologically similar.

These considerations lead to our third hypothesis:

HYPOTHESIS 3.—*The greater the number of indirect ties among the innovations in a niche, the lower the likelihood that an innovator will enter that niche at a point in time.*

While we have argued that indirect ties are the crucial structural determinant of the level of competition within the niche, direct ties are still a meaningful attribute of niche structure. Organizational and evolutionary theories of the firm (March 1988; Nelson and Winter 1982) highlight the role of local search behavior in understanding technological evolution. The basic claim of these theories is that resource constraints and embedded organizational routines restrict the areas for innovation that an organization may successfully pursue. This claim can be framed structurally by considering the number of nonfocal innovations, or alternatively the number of direct ties, within the niche. The more that the focal innovation is directly connected to other innovations, the more that the focal innovation is within the local search domain of other members of the technological community. This idea leads to our fourth hypothesis:

HYPOTHESIS 4.—*The greater the number of direct ties within the niche, the greater the likelihood of a new entrant into the niche.*[5]

IV. MEASURING THE NICHE

Having elaborated the framework and a set of theoretical propositions, we now present a way to operationalize the basic features of the technological niche and the process of niche entry. Within our framework, we require a methodology capable of identifying innovations and the technological connections between them. Our approach is to rely on information contained in patent issues, which grant innovators the legal rights to commercially exploit their inventions. Patents provide a useful means for identifying innovations since they are only granted to products, processes, or designs that are judged by the Patent Office to be industrially useful and nonobvious to those trained in the current state-of-the-art of the relevant technological domain. Patent applications not judged to represent novel technologies are denied.

Patents identify the technological ties between innovations. As part of the application procedure, patentees must list all previously issued U.S. patents that serve as important technological building blocks for the innovations for which they seek approval. Furthermore, it is the role of the

[5] Alternatively, this hypothesis might be formulated in terms of the number of actors within a niche rather than in terms of the number of direct ties. However, we believe that the number of ties is more appropriate, because it takes into account the intensity of a particular actor's search within the area of a focal innovation. We use patents and patent citations to operationalize the niche, and these two quantities (the number of actors and the number of innovations in a niche) rarely differ (see n.8 for the exact proportions of "repeat citations" in the data used for our analysis).

patent examiner to verify that the lists included in the patent application encompass all relevant existing innovations. Such listings are referred to as "prior art" citations, which are an integral part of the patent process in the United States. The citation process is legally important, because it limits the claims of the patent under consideration; the technological domain of the current patent extends only to the point where the prior art ends. The innovator has a legal claim only to the aspects of the patent that do not overlap with the technological contents of the cited patents (see Office of Technology Assessment and Forecast 1976, p. 167).

In our framework, each time a new patent is issued, the patented innovation both enters existing niches (by virtue of overlapping with the technologies represented by previous patents) and represents the emergence of a new egocentric niche. As time progresses, future patented innovations may cite the focal innovation, in which case its niche expands. For example, in figure 1 innovations 3 and 4, which are patented prior to the focal innovation, are included in the niche once the focal innovation is patented. These two innovations represent work that the focal innovation cited as prior art. Innovations 5–7 represent later niche entrants; these innovations cited the focal innovation.

A citation thus designates the focal innovation as a technological precursor to a novel technology. In addition, the Office of Technology Assessment (1976) asserted that the more cites that an innovation receives, the more important that innovation was in the advancement of technological knowledge. The literature has corroborated this assumption. For example, Trajtenberg (1990) found that patent citations were accurate indicators of technological importance in the computed tomography industry, and Albert et al. (1991) found a positive correlation between the number of citations that a patented innovation received and the technological importance that experts ascribed to that innovation. Several cross-sectional studies document a correlation between citations and economic performance. For example, Narin, Noma, and Perry (1987) found high correlations (ranging from .6 to .9) between the possession of a frequently cited patent portfolio and changes in corporate financial measures such as increases in company profits and sales (additional studies are reviewed in Basberg [1987]). In addition to these studies highlighting the relationship between citations and the (perceived) importance of an innovation, the fact that citation analysis is now used by corporations to analyze the technology portfolio of their competitors, to provide insight into likely future market strategies, and to compare productivity within or between firm laboratories further supports the use of patents as proxies for innovative activity (Eerden and Saelens 1991).

While academic research has validated the use of patent citation data as a meaningful reflection of a number of features of the innovative activities of firms, caution must still be exercised when using patents to identity innovations and the technological ties between them. Innovators may be less willing to patent some types of innovations than others (Levin et al. 1987). Furthermore, there are sometimes industry-specific means that innovators can use to protect their intellectual property.[6] For these reasons, it is not surprising that researchers have found interindustry variance in the tendency to patent (see Scherer 1984). To the extent that innovators do not seek patents for innovations, the use of patents to operationalize the composition and structure of the technological niche will be less encompassing. Clearly, the researcher must be sensitive to the validity of patents as indicators of innovations and the relationships among innovations in the context that is studied. With this admonition in mind, we turn to the empirical setting for our study, the semiconductor industry.

V. THE SEMICONDUCTOR INDUSTRY

The semiconductor industry began with the invention of the point-contact transistor at Bell Laboratories in 1947. The industry has evolved to include a heterogeneous population of firms, including large captive producers (e.g., IBM),[7] diversified merchant producers (e.g., Motorola), and specialized firms that concentrate on a single technology or market niche (e.g., Bipolar Integrated Technology). European and Japanese organizations have also actively participated in developing semiconductor technologies since the 1950s. In addition, while private firms have conducted a large majority of the innovation in semiconductor technology, national governments and universities have also developed and patented

[6] For example, in microelectronics, the industry that we examine, the Semiconductor Chip Protection Act of 1984 enables innovators to apply for copyrights to protect semiconductor mask works, which are in essence the designs of semiconductor chips' circuitry. However, there are reasons to think that innovators are still likely to seek patents for their devices. First, the period of copyright protection is only 10 years since the time at which the mask work is registered with the Copyright Office or it is first commercially exploited, which is shorter than the 17-year period of patent protection. Further, the Semiconductor Chip Protection Act does not prevent the innovator from receiving both copyright and patent protection for the same invention. Generally, it is thought that the statutory requirements for patents, novelty and nonobviousness, make patents more difficult to obtain than copyrights (for a discussion of the relationship between copyrights and patents for semiconductors, see Ladd, Leibowitz, and Joseph [1986]).

[7] Captive manufacturers are firms that produce for internal use rather than for sale on the open market. IBM is a captive producer because the vast majority of its semiconductors are consumed internally.

technologies. Thus, the semiconductor industry encompasses a range of actors based in many different nations, creating technological networks that span national boundaries and organizational forms.

We have collected all U.S. semiconductor device patents granted to worldwide semiconductor innovators and manufacturers for 16 years, from 1976 to 1991.[8] Previous research suggests that the U.S. patent system is the most complete for analyzing international technology. The United States is widely recognized as the world's largest technological marketplace (with 50% of patents granted to foreign applicants; Albert et al. 1991). Patent information provided by the U.S. Patent Office is available back to 1976 from the Lexis/Nexis on-line database.

As support for the use of patents to examine technology and technological change in the semiconductor industry, we note that all of the landmark innovations in semiconductor technology have been patented (Wilson, Ashton, and Egan 1980). Moreover, during the majority of the time period that we studied, certain semiconductor producers, most notably Intel and Texas Instruments (TI), aggressively litigated to protect their intellectual property. Indeed, the popular press estimated that TI earned some $1 billion in royalties from infringement lawsuits (Orenstein 1992). TI's patent royalties reached the point that the company reported them as a separate line item on its income statement. In addition, as Japanese producers gained familiarity with the U.S. legal system, they too became more assertive in filing infringement cases (for example, Fujitsu recently opted to file a countersuit against TI rather than to pay royalty fees; Helm 1992). The apparent importance that semiconductor firms placed on patents and patent rights suggests the validity of using patent information as operationalizations of the central concepts of our analysis.

VI. ANALYSIS

To assess our hypotheses, we model the citation rate for existing patents or, in theoretical terms, the process of niche entry and hence extension. Each spell begins when a patent is issued or cited and ends when it is next cited.[9] We employ the proportional hazards model introduced by

[8] Under the U.S. system, patents are filed according to major class and subclass. Semiconductor device patents include all subclasses of primary class 357. Patents are typically filed in one primary class/subclass combination but are also cross-classified in additional locations. We include in our sample all patents filed in primary class 357.

[9] We experimented with alternative event definitions. For example, we performed analyses in which we did not end a spell when a self-citation occurred (i.e., when a focal patent was cited by its owner). This event definition can be defended on the grounds that a self-citation is substantively less meaningful than a citation from another actor, because it does not imply that an additional actor has decided to enter

Cox (Kalbfleisch and Prentice 1980). The equation that we estimate takes the following specification:

$$r(t) = h(t)\exp[\boldsymbol{XB} + \boldsymbol{Y}(\boldsymbol{t})\boldsymbol{S}], \quad (1)$$

where $r(t)$ is the transition rate or hazard of niche entry, $h(t)$ is an unspecified baseline rate for the transition, $\boldsymbol{X}$ is a matrix of time-constant covariates, $\boldsymbol{Y}(\boldsymbol{t})$ is a matrix of time-varying covariates, and $\boldsymbol{B}$ and $\boldsymbol{S}$ are vectors of unknown regression parameters. Because $h(t)$ is an unspecified step-function, the Cox model offers an extremely flexible means for modeling time dependence. While the Cox model accounts for interarrival time dependence (i.e., the time from when the patent is granted to the time at first entry and then the time between subsequent entries) with an unspecified baseline rate for the transition, the time since last arrival is not the only form of time dependence that is likely to affect the rate of citation. In addition to modeling interarrival times, we also include two clocks that accelerate the baseline rate. First, we include a variable (updated monthly) to denote the calendar time. Second, assuming that firms are more likely to enter a niche after they become aware of it, the composite baseline should increase as a function of the time since the patent at the center of the niche was introduced. We therefore include a variable in the model to denote the time that has passed since the introduction of the focal patent (the age of the patent, also updated monthly). However, because we expect the relevance of a patent to decrease with the time since it was introduced, we include an age-squared variable as well to allow for nonmonotonicity.

Our theoretical framework emphasized three attributes of the technological niche: the quality of the focal innovation in a niche, the attributes of the actors associated with the niche, and the structure of relations among the innovations in the niche. We now introduce the covariates that we include in the model to represent each of these features of the niche.

The quality of the focal innovation.—The difficulty that industry observers have in inferring the comparative quality of innovations almost necessarily implies the absence of a completely adequate means to control

the niche. Based on a similar logic, we considered a second alternative in which a spell ends only if the focal patent is cited by a new actor rather than one that has previously cited the focal patent. Again, it might be that a citation from an additional actor is a more significant event than a repeat citation, because it indicates that an additional actor has chosen to enter the niche. However, only 5.3% of the spells end in self-citations, and only 4.6% of the spells end in repeat citations by nonfocal actors. Consequently, while there may be theoretical reasons for considering alternative event definitions, in practice the results were unaffected by the different definitions of the dependent variable.

for the quality of an innovation. We see three possible ways to respond to this difficulty. One is to forgo any attempt to control for quality, under the assumption that what is not observable cannot have an effect on the likelihood of niche entry. A second approach is to treat quality differences across patents as unobserved heterogeneity and then to devise some method for controlling for this unobserved heterogeneity. A third possibility is to rely on one of the measures of quality that has been put forth in economic analyses of patents as indicators of innovative activity. In our analysis, we have chosen the second and third approaches, which both suggest the same control variable for quality.

In their discussion of unobserved heterogeneity, Heckman and Borjas (1980) noted that unobserved differences across units are likely to result in occurrence dependence. A frequently cited example of this type of unobserved heterogeneity arises in the context of research on job mobility. If there is unobserved heterogeneity across individuals in their likelihood of shifting jobs, then an occurrence-dependent term (i.e., the number of times that someone has changed jobs in the past) will have a positive effect on the rate of job mobility. Heckman and Borjas argued that one way to account for such unobserved differences is to include as a control variable the number of previous realizations of the dependent variable. Applying Heckman and Borjas's logic to our analysis of patents, we include as a covariate the number of times that a patent has been cited, controlling for the time that the patent has been at risk of being cited.

While econometric work on unobserved heterogeneity suggests the inclusion of a variable denoting the number of times that the patent has been cited, so too does economic research on patents as indicators of innovative activity. In particular, Trajtenberg (1990) employed the number of citations received by a patent over a given time interval as a measure of that patent's quality. By including the number of citations received as a covariate (while also controlling for time dependence in the form of calendar time, the age of the patent, and the age of the patent squared), we thus include as a covariate the measure of quality that has been put forth in the economics literature. While we wish to avoid equating an occurrence-dependent term solely with quality differences, since unobserved heterogeneity could be due to other factors, the fact that we have included the measure that others have used to capture quality should serve as a counter to the alternative hypothesis that many of our results can be explained by unobserved quality differences between patents.

Attributes of niche occupants.—We have argued that an important characteristic of the actors within a niche is their status. Recall that we define an actor's status at a particular point in time as its contribution to the advancement of technological knowledge up to that time. Consistent with this definition, we measure an actor's status as a proportion related to the number of citations that the actor has received on all of its semiconductor device patents during the 12-month interval prior to the month in which it introduces a patent. A greater score on this variable implies a greater contribution to the advancement of technological knowledge over that time period. We do not measure status as a simple count, because an actor's portfolio of patents enlarges over time, thus increasing the number of patents "at risk" of a cite. This procedure would result in status increasing merely as a function of time. For example, in month 16 an actor can receive citations on patents only during a 15-month time period, but in month 36 it can receive citations on patents that it issued over a 35-month time period. To correct for the expanding risk set, we divide the number of cites to an actor over a given 12-month interval by the cites to all actors during that window. As a consequence of this standardization, an actor's status can range from "0," if it has received no citations during a given window, to a maximum of "1," if it has received all of the citations made over the previous year. In the context of our data, the highest status organizations have scores of approximately .1, indicating that they had received 10% of the citations made over a one-year period.

Hypothesis 1 anticipated a positive relationship between the status of the focal organization (i.e., the owner of the focal patent) and the rate at which other organizations choose to enter its niche. We thus include as a covariate the status of the focal organization at the time of its most recent entry into the focal patent's niche. In general, the value of this covariate will be the focal organization's status at the time that the focal patent was approved. However, if the focal inventor reenters the niche by introducing a patent that cites the focal patent, we update the variable to reflect the focal actor's status at the time of its most recent entry into the niche.[10]

To clarify the definitions of the variables in the event-history analysis, we refer the reader to figure 4 and table 1. Figure 4 presents a hypothetical niche that expands over time. Table 1 presents the spell data that would correspond to such a niche. The first spell begins when the focal patent is granted to organization C. At this time, organization C has a status of .04, and thus the covariate denoting the status of the focal inventor at the time of its most recent entry into the niche takes the value

[10] Clearly, this is not the only coding rule that one might apply. One might, for example, update the focal actor's status whenever it changed. However, such a coding rule was impractical, because many actors change status monthly as new citations arrive and old citations are dropped (these are typically small changes).

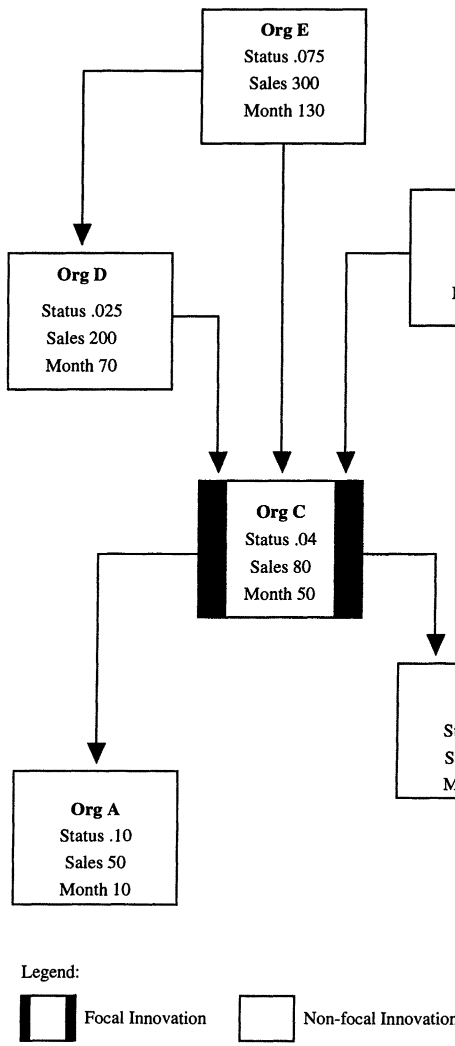

FIG. 4.—Hypothetical niche and attributes of organizational actors from which the spells in table 1 are constructed. Each box represents a patent and provides information on the month in which the patent was issued as well as the status and sales of the patent's owner at that month.

TABLE 1

SPELLS CONSTRUCTED FROM THE HYPOTHETICAL NICHE IN FIGURE 4

Variables	Spells 1	Spells 2	Spells 3	Spells 4
Time clocks:*				
Age of patent	0	20	50	80
Age of patent squared	0	400	2,500	6,400
Calendar time	50	70	100	130
Unobserved quality of the focal patent:				
N of patents that cite the focal patent	0	1	2	3
Attributes of actors within the niche:				
Status of focal organization	.04	.04	.06	.06
Average status of nonfocal organizations whose patents are cited by the focal patent	.075	.075	.075	.075
Average status of nonfocal organizations that cite the focal patent	0	.025	.025	.05
Sales of focal organization	80	80	100	100
Average sales of nonfocal organizations whose patents are cited by the focal patent	75	75	75	75
Average sales of nonfocal organizations that cite the focal patent	0	200	200	250
N of alliances entered into by the focal organization	0	0	0	0
N of self-citations by the focal organization	0	0	1	1
Attributes of the niche structure:				
N of indirect ties	0	0	1	2
N of patents cited by the focal patent	2	2	2	2

* Values listed are at the start of the spell.

.04. This value implies that in the 12 months prior to month 50, the month in which the focal patent is introduced, organization C received 4% of all the citations made. The first spell ends when the focal patent is cited by organization D in month 70. The covariate for the status of the focal inventor remains the same for the duration of the second spell, which ends in month 100 when organization C reenters the niche with a self-citation. On account of this reentry, we update the value of the covariate of the focal inventor to reflect the fact that its status has changed from .04 to .06. This variable has a value of .06 for the duration of the third and fourth spells.

Hypothesis 2 posited that the status of the nonfocal inventors in a niche would have a positive effect on the likelihood of new entrants into that niche. To assess the effect of the status of the nonfocal actors, we include two covariates: the average status of the nonfocal innovators with patents that are *cited by* the focal patent and the average status of the nonfocal innovators with patents that *cite* the focal patent. We divide the status of the nonfocal innovators into these two components because of the asymmetry implicit in the patent citation process. Our theoretical framework suggests that a citation from a high-status actor ought to be a more meaningful event than a citation to a high-status actor. If a high-status actor cites a focal patent, that actor implicitly acknowledges the dependence of its innovation on the technologies represented by the focal patent. In contrast, if a focal patent cites the innovation of a high-status actor, this implies only that the focal patent is in a technological area that the high-status actor regards as important; such a cite from the focal patent to the innovation of a high-status actor does not imply any acknowledgment on the part of the high-status actor of the focal patent's contribution.

Once again, figure 4 and table 1 show how these two variables are constructed. The focal patent in figure 4 cites two innovations. The average status of the owners of these patents is $(.10 + .05)/2 = .075$. The average status of the nonfocal innovators cited by the focal patent maintains this value for all of the spells. In contrast, the average status of the nonfocal innovators that cite the focal patent changes each time an additional organization enters the niche. In the first spell, the focal innovation by definition has no citers, and thus the value of this variable is 0 until the focal innovation is cited by organization D. Since organization D's status is .025, this variable has a value of .025 for the second spell. The value remains the same for the third spell since the reentry of the focal innovator into the niche does not affect this variable. However, when the focal patent is cited by organization E, this variable changes in value to .05, the average of organization D's status and organization E's status.

While status is the actor attribute of greatest theoretical interest, we recognize that it is not the only one that may be relevant to the process of niche entry. Another important attribute is the market presence of the organizations in the niche. Just as an organization's status may be a signal of the technological significance of its innovations, so sales may be a signal of the market significance of its innovations. There may be other reasons why an organization's market presence would affect the rate at which its technologies are developed, but we are less interested in discriminating among alternative explanations than we are in including market presence as a control. Because it seems reasonable to believe that sales and status will be correlated, greater confidence can be placed in a status effect if it can be shown to have explanatory power in excess of an organization's market presence.

Motivated by these considerations, we admit in the analysis the market sales volumes (in billions of dollars) for the merchant and captive semiconductor makers for which we were able to obtain this information. Data on the annual sales of merchant semiconductor firms between 1981 and 1991 were supplied by Dataquest, a consultancy and market research firm with clients in high-technology industries. Data on the estimated dollar value of production volume for the major captive producers over this period were obtained from the annual status reports issued by the Integrated Circuits Engineering Corporation (McLean 1981–91). Like our measures for organizational status, our measures for organizational sales are based on the time of an organization's most recent entry into the niche. However, unlike our status measures that are updated monthly, the sales data are available only annually. Thus, we include as a variable the sales volume of the innovator of the focal patent in the year prior to its most recent entry into the niche. We also add variables representing the average sales of all of the nonfocal organizations that are cited by the focal patent and the average sales of all the nonfocal organizations that cite the focal patent. Each time a new innovator enters a niche, this variable is changed to reflect the sales of the entering organization (measured at the year prior to entry).

There are two complications with the sales data. First, while the Dataquest data account for over 90% of worldwide semiconductor sales and offer the most complete information available, they are not exhaustive. Dataquest attempts to collect data on all firms producing more than $10 million in sales (approximately .02% of the market in 1991), but it does not track sales for all firms producing less than this dollar amount. For firms not included in the database, we assign a sales volume of zero. In so doing, we assume that sales levels of less than $10 million are not a stronger signal of market potential than zero sales, such as would by definition be true of nonproducing assignees (e.g., universities, government agencies, etc.). As justification for this decision, we note that the total sales volume in the industry ranged from $15.9 billion in 1981 to $55.5 billion in 1991, and the mean sales for a firm in the database are $473 million, so zero sales seems a sufficiently close approximation for the excluded firms. The second complication is that, while we have semiconductor patents from 1976, we have data on sales volume only from 1981. Excluding spells affected by missing data results in the elimination of 47% of the sample, quite possibly biasing the results. Therefore, we imputed missing sales data according to the multiple-imputation procedure advocated by Rubin (1987).[11]

[11] A distinctive feature of Rubin's multiple imputation procedure is that it introduces a random component into the imputation to reflect the uncertainty about the "true" parameter values underlying the coefficients that one uses for the imputation. In our analysis, we used a regression model to impute the missing sales data in year $t - 1$ from observed (or imputed) sales in year t. We repeated this procedure until we had a complete data set (i.e., complete sales information for all firms going back to 1975).

We include two additional control variables that reflect other aspects of the actors in a niche. First, we include a variable that is the number of times that the focal organization cites itself. We noted earlier the possibility that a citation by the innovator of the focal patent might not represent as significant an event as a citation by an independent firm. Thus, we control for self-citations in the analysis. The final attribute of the actors in the niche that we include is the total number of patent license, patent cross-license, technology exchange, and second-source agreements that the focal organization entered prior to its most recent entry into the niche.[12] We include the number of strategic alliances as a control variable, because the types of interorganizational relationships captured in this variable are likely to affect the degree to which the technology owned by an organization diffuses.[13] Specifically, we expect that an organization's participation in interorganizational relationships increases the amount of overlap between its innovative efforts and those of the organizations with which it is partnering. This overlapping effort may increase the degree to which other organizations build on the focal organization's patents. The data for this variable were collected by scanning every edition of the trade publication *Electronic News,* a weekly periodical that has a section devoted to the semiconductor industry, for the time period covered by the focal patents in our study. *Electronic News* is probably the most comprehensive single source for information about collaborations among semiconductor firms.[14]

Attributes of niche structure.—While hypotheses 1 and 2 considered the effects of status on niche entry, hypotheses 3 and 4 were concerned with the relationship between the structure of the niche and the rate

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We then constructed another complete data set following the same procedure. Rubin (1987) explains how parameter estimates from two or more such complete data sets can be combined to provide unbiased estimates of coefficients and their variances.

[12] Second-source arrangements are a common practice in the semiconductor industry. A formal second-source agreement occurs when one firm licenses another to manufacture one of its products, resulting in a nearly identical copy of the licensor's design. This practice helps to guarantee users that the product will be reliably supplied.

[13] Some of these agreements (cross-license and technology exchange deals) are symmetric in the sense that each firm licenses their patents or exchanges their technology with the other. The others, license and second-source deals, are asymmetric, because one firm is the licensor and the other is the licensee. Because we are interested in controlling for other factors that may lead to the diffusion of an organization's technology (and hence an increase in the rate at which its patents are cited), we increment this variable for both firms in the case of symmetric deals but only for the licensor in the case of second-source and license deals.

[14] While *Electronic News* is the most comprehensive source for interfirm collaborations, it is unlikely that the data on alliances is complete. In particular, we suspect that we have missed partnerships between small firms and especially small firms based outside the United States.

of entry. Specifically, hypothesis 3 stated that indirect ties among the innovations in a niche are expected to have a negative effect on the likelihood of a new entrant. The argument is that the competitive intensity in a niche is a positive function of the number of indirect ties in that niche, controlling for the number of direct ties. Therefore, we include as a covariate in the analysis a count of the number of indirect ties among the innovations in a niche (see fig. 4).

Hypothesis 4 speculated that the number of direct ties in the niche would have a positive effect on the likelihood of a new entrant into the niche. As with the sales and the status of the nonfocal innovators in the niche, direct ties can be decomposed into two components: (1) the number of patents that the focal innovation cites and (2) the number of patents that cite the focal innovation. The previous discussion of quality differences across patents suggests that there is an identification problem encountered in interpreting the number of citations received by the focal innovation. While the number of citations to the focal innovation could represent the degree to which the focal innovation is in the local search domain of other actors, it could also be a proxy for unobserved heterogeneity or patent quality differences. Thus, this parameter cannot be given a unique interpretation. While the interpretation of an effect for the number of citations *going to* the focal patent is confounded by alternative processes that may be proxied by this quantity, the number of citations *made by* the focal innovation can be clearly interpreted. The more patents that the focal innovation cites, the more that the focal innovation is within the local search domain of those within the technological community. Accordingly, we include the number of citations made by the focal patent as a test of the hypothesis 4.

We reiterate that our sample includes all semiconductor device patents between 1976 and 1991. While these data provide the opportunity for a longitudinal analysis, it is important to point out that the arbitrary lower bound of 1976 leads to left censoring. When a niche emerges, it includes not only the focal patent but also all of the patents that the focal patent cites. If any of these patents were issued prior to 1976, they would be excluded from the data and thus not captured in the demarcation of the focal patent's niche. To minimize the potential biases from left censoring, semiconductor device patents issued between 1976 and 1981 were not included in the analysis as focal patents but only as potential cites of patents issued from 1982 to 1991. Given that the product life cycle in the semiconductor industry is typically estimated to be three to five years from introduction to maturity (McClean 1981–91), we believe that a six-year window is fairly conservative. We have experimented with the length of this window, and the results that we report are robust across shorter and longer intervals. In total, our sample contains 4,048 patents,

TABLE 2

FREQUENCY OF EVENTS PER PATENT

N of Events	Frequency
0	1,037
1	668
2	483
3	289
4	174
5	111
6	72
7	32
8	34
9	25
10+	58

NOTE.—An event occurs when a subsequent patent enters a focal patent's niche; each event constitutes a completed spell.

TABLE 3

DESCRIPTIVE STATISTICS FOR VARIABLES

Variables	Mean	SD	25th Percentile	75th Percentile
Quality of the focal innovation:				
N of cites received by focal patent	1.743	3.092	0	2
Attributes of niche occupants:				
Status of focal innovator	.030	.024	.005	.048
Average status of nonfocal innovators cited by the focal patent	.020	.020	0	.033
Average status of nonfocal innovators that cite the focal patent	.013	.019	0	.026
Sales of focal innovator	.913	1.246	0	1.361
Average sales of nonfocal innovators that are cited by the focal patent	.335	.553	0	.415
Average sales of nonfocal innovators that cite the focal patent	.723	1.132	0	1.233
Self-citations of focal innovator	.453	.923	0	1
Alliances formed by focal innovator	5.789	6.976	1	8
Attributes of niche structure:				
N of citations made by the focal patent	2.278	2.142	1	3
N of indirect ties:				
Niche size = 2 or 3 (*N* = 3,244)	.164	.440	0	0
Niche size = 4 or 5 (*N* = 2,154)	.617	1.010	0	1
Niche size = 6 or 7 (*N* = 1,171)	1.432	1.741	0	2
Niche size = 7 or 8 (*N* = 645)	2.403	2.592	0	3
Niche size ≥ 9 (*N* = 753)	5.678	5.269	2	8

of which 2,983 represent focal patents (i.e., were issued after 1982). Table 2 presents descriptive information on the number of entries (completed spells) per patent. For example, 483 patents experienced two complete spells (i.e., two subsequent patents entered their niche). Table 3 presents descriptive information on critical independent variables. In addition to the means and standard deviations, we present values for the 25th and 75th percentiles, because the interquartile range is less sensitive than the standard deviation to outliers and to the assumption of normality. We report the distribution for the number of indirect ties at various levels of niche size (i.e., the number of citations from the focal patent plus the number of citations to the focal patent), since the number of possible indirect ties is contingent on the number of direct ties.

VII. RESULTS

We estimate the waiting time model specified in equation (1) using TDA 5.2 (Rohwer 1993). Hazard rate estimates are presented in table 4. The coefficients reported in this table indicate how a one-unit change in an independent variable serves to multiply the rate of niche entry.

In columns 1 and 2 of table 4, the effect for the status of the owner of the focal patent is positive and statistically significant. However, when the attributes of the nonfocal innovators and the sales of the owner of the focal patent are included in the full model (col. 3), this effect is no longer statistically significant. We had suspected that the lack of significance may have resulted from a high correlation between the sales and status of the owner of the focal patent, but the correlation between these two variables is only .55. Thus, we cannot reject the null hypothesis that the status of the focal innovator has no independent effect on the likelihood of a new entrant into the niche of the focal patent.

In contrast, the average status of the nonfocal innovators that cite the focal patent and the average status of the nonfocal innovators that are cited by the focal patent both have positive and statistically significant direct effects on niche entry in the complete model. These findings indicate that the relationship between organizations in a niche can be commensalistic: When patents owned by high-status actors enter a niche, they attract other innovators, thus enhancing the status of the focal actor. Moreover, the status of those that cite the focal patent has a greater effect on the hazard of niche entry than does the status of those who are cited by the focal patent. To illustrate the difference, we consider how an interquartile shift in both variables multiplies the rate of entry. An interquartile-size increase in the average status of the citers of the focal patent augments the rate of niche entry by 30% ($\exp[10.14 \times .026] = 1.302$). In contrast, an interquartile-size increase in the average status of

TABLE 4

PARAMETER ESTIMATES FOR THE HAZARD OF NICHE ENTRY

Variable	Model 1	Model 2	Model 3
Time clocks:			
Age of patent	.0549** (.0058)	.0458** (.0058)	.0453** (.0058)
Age of patent squared	−.0001** (1.6e-5)	−.0001** (1.8e-5)	−.0001** (1.8e-5)
Calendar time	−.0125** (.0006)	−.0086** (.0007)	−.0089** (.0007)
Quality of the focal innovation:			
N of cites received by focal patent	.1118** (.0064)	.1030** (.0065)	.1019** (.0066)
Attributes of niche occupants:			
Status of focal innovator	1.3937* (.6555)	1.6508** (.5934)	.7780 (.6605)
Average status of nonfocal innovators cited by the focal patent	. . .	2.1555** (.8239)	2.5329** (.8326)
Average status of nonfocal innovators that cite the focal patent	. . .	10.0709** (1.4007)	10.1462** (1.4033)
Sales of focal innovator	0.0292* (.0148)	. . .	0.0474** (0.0151)
Average sales of nonfocal innovators cited by the focal patent	. . .	.1710** (.0332)	.1644** (.0332)
Average sales of nonfocal innovators that cite the focal patent	. . .	.0760** (.0230)	.0757** (.0231)
Self-citations of focal innovator	−.0006 (.0165)	.0382* (.0163)	.0276 (.0168)
Alliances formed by focal innovator	.0051* (.0023)	.0037 (.0022)	.0022 (.0023)
Attributes of niche structure:			
N of indirect ties	−.0557** (.0078)	−.0467** (.0080)	−.0464** (.0080)
N of cites made by focal patent	.0933** (.0066)	.0692** (.0071)	.0734** (.0072)

NOTE.—SEs in parentheses.
* $P < .05$.
** $P < .01$.

those cited by the focal patent increases the rate of niche entry by only 8.7% (exp[2.53 × .033] = 1.087). In other words, the effect of the average status of those who cite the focal innovation is more than three times the magnitude of the effect of the average status of those cited by the focal patent. The difference in the magnitudes of these coefficients is consistent with our interpretation that a citation to the focal innovation is an explicit recognition of the importance of that innovation and that a citation from the focal innovation indicates only that the focal innovation is proximate to the innovations of other actors.

Particularly interesting is the finding that the status of the nonfocal actors has a greater direct effect on the likelihood of niche entry than does the status of the focal innovator. Even in the model for which the sales of the focal organization are excluded from the analysis (col. 2 of table 4), the effect for the status of the nonfocal actors is greater than the effect for the status of the focal actor. While we had not anticipated this result, it is compelling to find that innovators have greater difficulty legitimizing their own innovations than drawing attention to the innovations of others. An actor's self-interest in the success of its own innovations almost undoubtedly compromises its ability to draw on its status for the purpose of attracting to its innovations the attention of other actors.

Although there is no statistically significant direct effect for the status of the focal innovator on the likelihood of entry, a comparison of the results in columns 1 and 3 of table 4 reveals an important indirect effect of the focal organization's status. In column 1, when only the attributes of the nonfocal innovators are excluded, the effect of the focal owner's status on the likelihood of niche entry is positive and statistically significant. Indeed, the magnitude of the coefficient is approximately two times greater than in the full model. This finding implies that the status of the focal innovator significantly affects the probability that higher status (and larger) nonfocal actors will enter the niche, which in turn has a positive effect on the rate of niche entry. However, when we control for the status and size of these nonfocal actors, there is little direct effect of the focal owner's status. Together, the indirect effect for the status of the focal actor and the direct effects for the nonfocal actors underscore the importance of the sociotechnical context that is highlighted by the niche framework. The less that an actor is able to exploit its status to draw attention to its own efforts, the more that actor depends on the context in which its innovations are situated.

Now we turn to the results for the attributes of niche structure. As hypothesized, the parameter estimate for the number of indirect ties in a niche is negative, indicating that an increase in the number of indirect ties reduces the rate of niche entry. Controlling for the number of direct ties in the niche, each indirect tie lowers the rate of niche entry by 4.5% ($\exp[-0.0464] = .955$). The negative coefficient as well as the level of significance for this variable suggest that the number of indirect ties does reflect the competitive intensity in the niche. Thus, technological domains that are "crowded" in the sense that the innovations in them lack differentiation are ones that potential entrants either avoid or are unable to enter.

Finally, the coefficient for the number of cites made by the focal patent has a positive effect on niche entry. This finding supports the local search hypothesis, which suggests that organizations continue to work in the domains in which they have had previous successes. The more that an innovation is within the local search domain of other organizational actors, the more likely is that innovation to become a foundation for future technological developments.

Turning briefly to the control variables, we find that the coefficients for the number of cites received by the focal patent is positive. Because this variable is an occurrence-dependent term, we urge caution in its interpretation. However, the fact that this measure has been used in the economics literature to control alternatively for unobserved heterogeneity or quality differences across patents should increase the level of confidence in the results. The estimate for the sales volume of the focal firm and the average of the sales volumes of the nonfocal firms in a niche both have positive effects on the rate of niche entry. The number of times that a firm cites its own patents does not have a statistically significant effect in the complete model. The final control variable, the number of strategic alliances in which a firm participates, is positive but not statistically significant in the complete model.

VIII. CONCLUSION

The sociology of technology has provided insight into the process of technical change by emphasizing the uncertainty inherent in the innovative process and by invoking the network metaphor to highlight the interconnections among the diverse array of actors involved in the development of technologies. However, as we have observed, a review of this literature raises three concerns. First, it is unfortunate the degree to which this literature has developed separately from the sociological work on organizations and markets, given that the vast majority of innovation takes place within (typically market-based) organizations. Second, the studies in this tradition tend to be retrospective and thus suffer from a selectivity bias. Third, while this tradition's preference for "thick description" has sensitized scholars to many intricate features of the innovative process, this description has often proceeded at the expense of generalizable, falsifiable propositions regarding the rate and direction of technical change.

In this work, we have sought to redress these shortcomings. While we have depended upon the social constructivists' emphasis on the inherent uncertainty underlying the innovative process and the "seamless web" connecting actors and innovations, our framework and hypotheses have drawn on insights from the organizations literature within sociology. Ecology and especially network theory have provided the tools to operationalize the technological niche, and, along with recent sociological work on markets, they have contributed to the formulation of a series of general hypotheses about how the properties of a niche and the actors within that niche affect the likelihood of entry.

In the hazard rate analysis, we found that the status of the focal actor did not have a statistically significant direct effect on the rate of niche entry, but it did exert an indirect effect. High-status focal actors were more likely to find their innovations in niches occupied by high-status nonfocal actors, and the status of these nonfocal actors increased the rate of niche entry. Since an organization's status derives from the degree to which others have entered the niches in which it is the focal innovator, this result indicates that an actor's status depends not only on the quality or importance of its past efforts but on the status of those with whom it is affiliated. This finding and the finding that the number of indirect ties in the niche (which proxied for competitive intensity) had a negative effect on the rate at which innovators enter are the ones that we regard as the most interesting. These results demonstrate that an organization's role in the process of technological change is meaningfully embedded in the sociotechnical context into which its innovations are introduced and developed.

Before concluding, we would like to draw attention to some features of this analysis that have so far remained only implicit, as well as to highlight some directions for future research. Embedded in our analysis has been a methodological proposition about the process of technical change. In the literature on technology, the distinction is often made between the rate, direction, diffusion, and adoption of innovations, and these phenomena have been explored in separate studies. While we acknowledge the conceptual separation of these areas, we do not subscribe to their analytical divorce. Technologies develop as they diffuse, and as they progress they become more attractive to potential adopters, affecting the pace at which the initial innovation is modified; thus, rate, direction, diffusion, and adoption are intertwined.

While this analysis has been carried out at the microlevel, we briefly comment on the macrolevel implications of the observed effects of status and sales insofar as they indicate possibilities for future research. If large and high-status organizations shape the course followed by technical change, then within any technological domain we should observe that as history progresses innovative activity will be increasingly conducted by large, high-status firms, since small, low-status firms will be more likely to find themselves following technological dead ends. Indeed, Schumpeter (1950) posited a similar macrolevel dynamic, although he invoked the monopoly power of large firms as an explanation for why such firms would be the drivers of technical change. This analysis suggests a similar empirical result but does not require that high-status organizations have monopoly power within their markets to gradually become the dominant forces in directing innovation. The relative contributions of status and monopoly power in shaping technical change could be observed if a technological domain could be studied from a period close to its inception. Biotechnology is one area that may afford the opportunity for such an exploration.

A second possible direction for future research would be an exploration of the connection between the technological ties that emerge among organizations in the elaboration of the technological network and the diverse array of interorganizational linkages. We expect that an organization's location in the technological network should both partially explain and be partially explained by these interorganizational relations.

Regardless of the direction of future research, the role-based ecology provides a sociological view of the rate and direction of technical change. We believe that these processes have yet to receive enough systematic research in sociology, given their importance in general and in particular their unique role in shaping the social organization of many economic activities.

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