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TECHNOLOGICAL LOCKOUT: AN INTEGRATIVE MODEL OF THE ECONOMIC AND STRATEGIC FACTORS DRIVING TECHNOLOGY SUCCESS AND FAILURE

MELISSA A. SCHILLING
Boston University

Technology markets often exhibit extreme path dependency, enabling random or idiosyncratic events to have dramatic effects on technology success or failure. However, these effects accrue in an ordered way: by impacting a set of factors that have predictable influences on technology adoption. Since firm strategy also impacts these factors, technology adoption is neither wholly random nor beyond the firm's control. In this article I build a model of these factors by integrating economics, strategy, and marketing research. The model yields important implications for the strategic development and deployment of technology.

In many markets there are forces encouraging the selection of a single (or few) technology standard(s). This standard—or "dominant design"[1]—may be embodied in a single product configuration, the system architecture of a family of products, or the process by which products or services are provided. Where an entrenched dominant standard exists, or where an industry is in the process of selecting a dominant standard, firms may be at risk of being locked out of the market. In markets that are in the process of selecting a dominant design, a firm may be technologically locked out because the technology standard it supports is rejected in favor of a competing standard. Alternatively, in markets where a dominant design already exists, a firm may be technologically locked out if it is unable to (or barred from) producing products compatible with the standard.

Occasionally, when a company's standard is rejected, the firm is able to reenter the market by adopting the dominant standard. Sony, for example, has been successful in producing and marketing VHS videorecorders after the market rejected its proprietary Beta standard. But some firms are locked out in both ways. For example, Nexgen, a CPU manufacturer, realized that it could not make CPUs identical to Intel's dominant standard. Intel's patent suits against rival AMD already had demonstrated that the company would defend its ownership over its proprietary design. Nexgen, instead, chose to market its own variant of the CPU, which was purported to have a slight speed advantage over the Intel architecture. Customers, however, were wary of using an alternative CPU, because the market was composed primarily of software and hardware that was optimized to run on the Intel X86 standard (in fact, the first version of Microsoft's office would not run on the Nexgen chip). Sales were very poor, and in 1996 the company sold its operations to AMD. Thus, the company was locked out of producing products conforming to Intel's dominant design, and its own product architecture was rejected by the market.

In this article I integrate several diverse streams of literature from industrial organization economics, strategic management, and marketing strategy to develop a model of the factors increasing the likelihood of technological lockout. I then use these factors to derive recommendations for how technology development should be managed in order to avoid lockout. I examine two forms of technological lockout: (1) the firm produces products representing or conforming to a technological standard that is subsequently rejected by the market, and (2) there is an existing dominant design and the

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[1] A dominant design is "a single architecture that establishes dominance in a product class" (Abernathy, 1978; Anderson & Tushman, 1990; Sahal, 1981).

firm is unable to (or barred from) producing or selling products conforming to this standard.

This research makes an important contribution both to theory development in this area and to managerial practice. The model provides testable research propositions about the interaction of external factors (industry conditions and competition) and internal factors (attributes and actions of the firm) in determining a firm's likelihood of being technologically locked out. This research also yields important implications for development project investment decisions and implementation mechanisms. For instance, with the model we gain insight into the desired timing of technology development and whether or not the firm should seek to actively diffuse or protect its technology. The focus of the research is the firm and its involvement in a particular technology market; broader issues pertaining, for instance, to technology trajectories that span multiple design generations, or other industry-level phenomena, are discussed in their relationship to the firm and technology of interest, but readers can find more in-depth discussion of such issues in Anderson and Tushman (1990), Arthur (1989, 1994), Dosi (1984, 1988), Nelson and Winter (1982), and related works.

I begin the article with a definition of technological lockout. Next I overview the relevant literature and derivation of the model and research propositions. Following that I discuss the implications this article has for both research and management. In the last section I draw conclusions from the article regarding random versus nonrandom effects, and the benefits of using an approach that combines an external and internal focus.

TECHNOLOGICAL LOCKOUT

In many industries a firm that chooses to delay or forego investment in new product development may quickly find itself unable to compete. In "fast-cycle" industries, where the life cycle of a product may be less than 2 years (Williams, 1992), products and their associated technologies rapidly become obsolete. Falling behind the technology frontier can be perilous to firms in these industries, and "catching up" can be extremely difficult and costly. As Reich eloquently quips, "Once off the technological escalator it's difficult to get back on" (1987: 64).

It is not only the pace of an industry, however, that may cause a firm or technology to become locked out of the market.[2] As Arthur (1989) points out, the path of a technology often is characterized by "nonergodicity" (i.e., small events may have a large impact on final outcomes). Although the quality and technical advantage provided by the technology undoubtedly influences its fate, other factors, unrelated to the technical superiority or inferiority of the technology, also may play important roles. For instance, timing may be crucial; early technology offerings may become so entrenched that a firm offering subsequent technologies, even if they are considered technically superior, may be unable to gain a foothold in the market. Another example of a factor that may impact the adoption of the technology is how, and by whom, the technology is sponsored. If, for example, a large and/or powerful firm aggressively sponsors a technology (perhaps even pressuring suppliers or distributors to support the technology), that technology may gain a controlling share of the market. Firms sponsoring alternative technologies may then be locked out.

Because technologies may demonstrate nonergodicity (or extreme path dependency) at first, one may infer that the processes of technology selection or technological lockout are unsuitable for modeling, because random or idiosyncratic events may significantly influence final outcomes. However, if we examine a number of well-known cases of lockout (e.g., Sony in its Beta technology, Next's personal computer, Philip's DCC standard in audiotapes, or Digital Research's CP/M operating system), a number of consistent patterns emerge. Although idiosyncratic events (or attributes) do influence final outcomes, their effects are indirect. These events are antecedents of a set of factors having fairly *regular* and *predictable* influences on the likelihood of technological lockout, and it is a straightforward matter to model the effects of this set of factors. Furthermore, other antecedents (such as firm strategy) also act on these factors. Therefore, although there may be events

[2] I use the term "technology" in the article to mean a way (or ways) of carrying through any economic purpose, and may be embodied in products and/or processes. As Arthur defines them, technologies "may exist as pure method or pure information; or they may be embodied in physical plant or machinery" (1994: 15).

influencing lockout that are beyond a firm's control, the firm may actively manage those that are within its control to tip the balance in its favor and minimize its likelihood of being locked out.

I define technological lockout here as a situation in which a firm finds itself unable to develop or competitively sell products to a particular market because of technology standards. For instance, there may exist an established technology architecture dominating the market that the firm is incapable of (or barred from) producing because of another firm's protection of the technology. Or, perhaps, the firm has simply fallen so far behind the state-of-the-art technology in a given market that it is unfeasible for the firm to catch up in order to produce a competitive technology. Lockout may occur over a matter of weeks or over a number of years. It is important to note that *not* being locked out is not the same thing as being "locked in." In many industries several standards may compete for years, even decades, without one technology being locked in as a dominant design. During that time frame, however, several other technologies may have been locked out.

Whatever the cause or time frame, being technologically locked out almost always has dire consequences. For companies that are diversified, being technologically locked out may mean withdrawal from a particular market. For example, Geoworks, a company that produced a graphical interface operating system called Ensemble, intended to market its product to IBM-compatible personal computer owners. However, the company released Ensemble 6 months after Windows was introduced (Windows also had the advantage of being tied to MS DOS), and it was unable to compete. Windows had already become the dominant operating system. Geoworks has now turned to specialized applications of its products, such as dashboard computers.

For undiversified firms, being locked out may cause the firm to be dissolved or acquired by another firm. For example, Micropro produced a popular word-processing program called Wordstar, which was the dominant word-processing program from 1979–1983. The program had been developed when CP/M was the most commonly used operating system, and its key virtue was its customizability for varying hardware platforms. However, after the IBM PC was released, Micropro began to lose market share to Microsoft Word and WordPerfect, whose programs were optimized for the IBM PC. The company then had to make a critical decision about what direction the market would take. Faced with the IBM PC, MS-DOS PCs that were not IBM compatible, CP/M-86, and new, low-cost Unix machines, the company bet that portability and ease of learning would be the key to regaining market share. The result was WordStar 2000, which was slow because it was written in C (instead of assembler) and had a poor user interface. It failed to recapture market share from either WordPerfect or Microsoft Word, which were both written in assembler and tied to the IBM PC—by this time the dominant architecture. Micropro is now virtually nonexistent; its only remains are its mailing lists and a 1-800 number for servicing existing customers.

Considering the dramatic impact technological lockout may have on a firm's bottom line, it is very important to understand the factors increasing the likelihood of technological lockout so that these factors may be included in the firm's decisions about investing in new technology development. A model of the factors that influence lockout should not only enable one to forecast the likelihood of lockout but to identify areas in which intervention may help a firm avoid lockout.

THEORY DEVELOPMENT AND PROPOSITIONS

To build a model of technological lockout, I reviewed a diverse range of literature related to standards, dominant design, new product development, and technology strategy. From industrial organization economics, the literature on increasing returns to adoption, "technological paradigms" (Dosi, 1988), network externalities, and compatibility yields insight into why industries often coalesce around a dominant design, rather than support multiple, competing technologies, and how that dominant design is chosen. The economics literature on patents (and other forms of legal control of proprietary technology) is also valuable in illustrating how these designs are protected and how the effectiveness of this protection varies across industries.

From the strategy literature, research on new product development and the resource-based view of the firm reveals the importance of organizational learning in improving the firm's new product development process, renewing the firm's core capabilities, and making the firm able to respond quickly to a changing technological environment. The marketing strategy literature provides research on the importance of timing in market entry, and both strategic management and marketing strategy yield insight into how technologies may be protected or diffused.

Since dominant design plays a critical role in both conditions of technological lockout, the next section overviews the forces that lead to industry coalescence around a single standard.[3]

Dominant Design

In many cases the rise of a dominant design exhibits a situation of extreme path dependency. When several technological options become available commercially, sequential adoption by commercial users may rapidly lead to the supremacy of a single option, whether or not it is technically superior (Arthur, 1989; England, 1994; Katz & Shapiro, 1986). It is interesting to note that this dominant design may also influence the nature of subsequent dominant designs. As a technology is refined and learning accumulates along a particular technology trajectory, it also shapes the problem-solving techniques used in the industry, often resulting in a very "sticky" technological paradigm that directs future technological inquiry in the area (Dosi, 1988). Market adoption of a dominant design, therefore, has very far-reaching implications. Adoption of a dominant design may be a result of some combination of the effects of increasing returns to adoption, pressures for compatibility, and/or government regulation and, in turn, influences the way these effects select future dominant designs.

Increasing returns to adoption. Complex technologies often exhibit increasing returns to adoption in that the more they are used, the more they are improved. An adopted technology usually generates revenue that can be used to further develop and refine the technology. Furthermore, as the technology is used, greater knowledge and understanding of the technology accrues as a byproduct, which may then enable both improvements in the technology itself and in applications of the technology. Finally, as a technology becomes more widely adopted, complementary assets are often developed that are specialized to operate with the technology. These effects can result in a self-reinforcing mechanism—increasing the dominance of a technology regardless of its superiority or inferiority to competing technologies. Arthur notes,

> When two or more increasing-return technologies "compete" then, for a "market" of potential adopters, insignificant events may by chance give one of them an initial advantage in adoptions. This technology may then improve more than the others, so it may appeal to a wider proportion of potential adopters. It may therefore become further adopted and further improved. Thus a technology that by chance gains an early lead in adoption may eventually "corner the market" of potential adopters, with the other technologies becoming locked out (1989: 116).

Increasing returns to adoption can be split into two categories of effects. One category consists of learning-curve advantages: as a technology is used, it is further developed and made more effective and efficient (Amit, 1986; Hall & Howel, 1985). A second category of effects is known as "network externalities" (or "positive consumption externalities"). In markets characterized by network externalities, the benefit a consumer derives from a good often depends on the number of other consumers purchasing similar items (Choi, 1994; Katz & Shapiro, 1986, 1992; Thum, 1994). Obvious examples of markets demonstrating network externalities are those involving physical networks, such as telecommunications, computers, and railroads. In these industries the market share of the technology circumscribes the boundaries of the consumer's available network (Garud & Kumaraswamy, 1993).

However, network externalities can arise in a number of other important ways. For example, as Katz and Shapiro point out, "Any technology requiring specific training is subject to network externalities; the training is more valuable if the associated technology is more widely adopted" (1986: 823). Network externalities may also appear in the form of increased availability or lower cost of auxiliary benefits, such as complementary products and after-sales service. For

[3] The strength of these forces may vary by industry and over time. In new or emerging markets, pressure for a dominant design may be weak because the market is still forming its expectations about what is desired in the new technology. Furthermore, in some markets the consumer desire for heterogeneity may outweigh the advantages of compatibility, leading to low pressure for a dominant design.

these reasons, industries characterized by network externalities have strong selection pressures to choose and conform to a single dominant design.[4]

Compatibility in the absence of network externalities. Even industries not characterized by network externalities may reap gains of compatibility and standardization. Economides (1989) demonstrates that even when network externalities are ruled out, equilibrium prices and profits in an industry may be higher under conditions of compatibility, providing a strong incentive for firms to conform to a dominant design. This situation occurs because competition is more intense under incompatibility, resulting in lower prices and profits. Farrell and Saloner (1985) also examine the benefits of industry standardization and describe how these benefits can "trap" an industry in an obsolete technology, even when there is a better alternative available, as long as there is incomplete information. In a sense, firms are afraid to gamble on a new technology when they are uncertain about the actions of other firms and, therefore, about the likelihood of the technology becoming a new standard. This "excess inertia" can be overcome through communication if the benefits of the new technology are distributed symmetrically among the competing firms. However, if firms stand to benefit asymmetrically from the new technology, communication may serve only to exacerbate the inertia.[5]

Government regulation. In some industries the consumer welfare benefits of having compatibility in technology have warranted government regulation and, thus, a legally induced adherence to a dominant design (Anderson & Tushman, 1990; Brock, 1975). This has often been the case for the utilities, telecommunications, and television industries, to name a few. Some have even argued that the consumer welfare benefits of compatibility justify government intervention in the standards used by computer hardware and software manufacturers. Where government regulation imposes a single standard on an industry, that standard necessarily dominates the other technology options available to the industry.

The technology decisions facing the firm are quite different, depending on whether the industry currently is seeking a dominant design or a dominant design is already entrenched. A firm can be locked out in either scenario, but the factors that influence the likelihood of lockout will be different. I explore each of these scenarios in turn.

Type I Technological Lockout

> *The firm produces products, in the absence of a dominant product design, that are subsequently rejected by the market as the market moves toward a dominant design.*

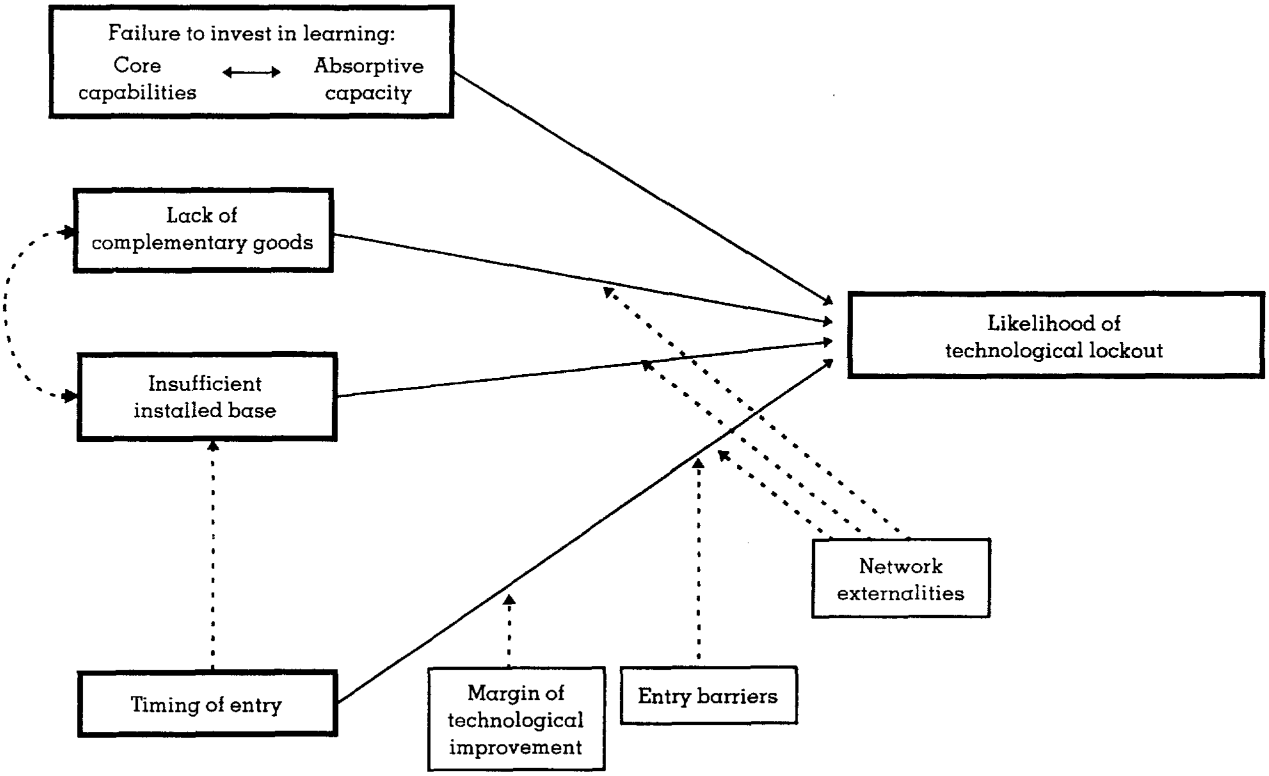
The market often rejects technology standards because (1) these standards fail to meet consumer expectations of quality, features, or price; (2) there are network externalities in the market, and the technology's installed base or availability of complementary goods is insufficient; or (3) the timing of market entry is either too early (in emerging markets) or too late (in established markets; see Figure 1). For example, Sony's Beta video standard, Philips DCC audio format, and Micropro's Wordstar word-processing software are all examples of technology designs that the market rejected in favor of a competing technology: VHS in videos, compact discs in audio formats, and MS Word and WordPerfect (assembler-based programs) in word-processing software.

Why would a firm be unable to produce a technology standard meeting consumer expectations? One reason might be that there is little consensus on what consumer expectations are. In this case firms gamble on what they perceive to be the best match to consumer expectations, and, because firms have different expectations, several different standards are produced (Barney, 1986). Some technology standards may better match consumer expectations than others, and a firm's standard may be rejected because the firm gambled on the wrong set of technology attributes. For example, in the early 1990s sev-

[4] Farrell and Saloner (1985) identify two types of inertia causing dominant designs to remain entrenched: symmetric and asymmetric. In the former, firms are unanimous in their preference of the new technology, but none is motivated sufficiently to initiate change. In the latter, firms differ in their preference for the new technology, but the total benefits of the change exceed the total cost; again, none is motivated sufficiently to initiate the change.

[5] Contrastingly, Katz and Shapiro (1992) identify conditions under which there may be insufficient inertia (or "insufficient friction," in their words), resulting in a bias toward new technologies at the expense of social welfare.

FIGURE 1
Factors Influencing the Likelihood of Type I Technological Lockout



eral companies were formed to develop pen-based personal digital assistants (PDAs)—palm-sized computers. However, since existing microprocessor and battery technology was not sufficient to enable duplication of all desktop computer functions on a computer small enough and light enough to be a PDA, only a subset of features could be included. Not having a high degree of consensus on what features consumers would be willing to pay for on a PDA, several companies (e.g., GO Corp., EO Corp., and Momenta) chose to develop designs that provided many functions (e.g., word processing, spreadsheets, and Internet connectivity) at a high price. None of these companies was able to attract many consumers, and each was dissolved. The companies that survived focused on technology designs that were more streamlined (e.g., U.S. Robotics Pilot) and were highly compatible with well-established desktop environments (e.g., the Pilot offers seamless integration with Windows, and the Apple Newton is compatible with the Macintosh operating system).

Sometimes consensus exists about what consumers want, but some firms are better able to provide the desired set of attributes in their product offerings than others. A firm may lack critical core capabilities needed to produce the desired features or level of quality in the technology offering (Barney, 1991). Furthermore, once firms identify the need for capabilities, some are faster than others at acquiring these capabilities.

Lack of Core Capabilities and Absorptive Capacity

The resource-based view of the firm and the literature on organizational learning and renewal reveal that, through investment in technology development and its associated learning, firms both expand their knowledge and skill base (or *core capabilities*) and improve their ability to assimilate and utilize future information (their *absorptive capacity*). The resource-based view of the firm also explains that the heterogeneous distribution of these capabilities and absorptive capacity is what often gives one firm an advantage over another. Failure to invest in this continuous learning results in a forfeiture of both the development of new capabilities and an increase in absorptive capacity. I discuss these two components of learning (which may be seen, respectively, as the content and process components of learning) separately below.

Core capabilities. A company's core capabilities are those that differentiate it strategically. It is a knowledge set embodied in four dimensions: (1) employee knowledge and skills, (2) technical systems, (3) managerial systems, and (4) values and norms (Leonard-Barton, 1992). As Leonard-Barton points out, the idea of core capabilities has been explained by many authors using a variety of terms, such as "distinctive competencies" (Hitt & Ireland, 1985; Snow & Hrebiniak, 1980), "core competencies" (Hayes, Wheelwright, & Clark, 1988; Prahalad & Hamel, 1990), "firm-specific competence" (Pavitt, 1991), "resource deployments" (Hofer & Schendel, 1978), and "invisible assets" (Itami & Roehl, 1987). Despite slight differences, each of these terms is meant to define a set of abilities that allows the firm to be competitive in the market, and this set of abilities is markedly influenced by the development projects chosen (or foregone) by the firm. Learning within a firm is cumulative and self-reinforcing. Firms will tend to use and build on their existing knowledge base rather than entering unfamiliar areas; therefore, "what the firm can hope to do technologically in the future is narrowly constrained by what they have been capable of doing in the past" (Dosi, 1988: 1130).

When a firm invests in the development of a new technology, it expands its existing knowledge base and experience, and it acquires new core capabilities. The core capabilities arising from new product development frequently are more important than the project itself (Bowen, Clark, Holloway, & Wheelwright, 1994). Meyer and Utterback (1993) point out that core capabilities enable a firm to develop whole families of products and successive platforms. For example, Digital Equipment Corporation's (DEC) effort to develop high-density disk drives in the 1980s resulted in the RA90 hard-disk drive. Although the RA90 was anything but a success, the knowledge DEC gained during its development laid the foundation for a generation of future products. In developing the RA90, DEC acquired state-of-the-art capabilities in making thin-film media and heads and in designing and assembling high-performance disk-drive systems. These capabilities significantly enhanced DEC's competitiveness (Bowen et al., 1994).

Alternatively, a firm that delays or foregoes investment in new technology development also foregoes development of new (or enhancement of existing) core capabilities. It may be because of forfeited core capability development that firms fall behind the technology frontier. Several authors have noted that firms that do not invest in new product development as a form of renewal of the company may find that previous core capabilities become core rigidities, limiting the firm's ability to respond to changing technology (Bowen et al., 1994; Leonard-Barton, 1992), which results in their products and processes becoming obsolete. The firm, unable to compete with its existing products and unable to respond to the changing technology, is locked out of the market.

Absorptive capacity. Absorptive capacity refers to the phenomenon whereby individuals, as they learn, increase their future ability to assimilate information (Cohen & Levinthal, 1990). The knowledge base possessed need not be directly related to the knowledge base being acquired for absorptive capacity to be affected. As Ellis's (1965) research into individual learning points out, learning skills may be transferred across fields of knowledge that are organized or described in similar ways; in a sense, learning engenders learning.

In addition to possibly creating a new core capability (as discussed earlier), a firm's investment in learning may facilitate the firm's future ability to acquire knowledge and to develop technologies through increasing the firm's absorptive capacity. Cohen and Levinthal posit,

> the ability to evaluate and utilize outside knowledge is largely a function of the level of prior related knowledge. At the most elemental level, this prior knowledge includes basic skills or even a shared language but may also include knowledge of the most recent scientific or technological developments in a given field. Thus, prior related knowledge confers an ability to recognize the value of new information, assimilate it, and apply it to commercial ends. These abilities collectively constitute what we call a firm's "absorptive capacity" (1990: 128).

The effects of absorptive capacity mean that a firm that foregoes investment in technology development may find it more difficult or expensive to develop technology in a subsequent period. This explains, in part, why firms that fall behind the technology frontier find it so difficult to catch up. Furthermore, firms not regularly investing in technology development may make bad choices when selecting projects to invest in; thus, learning contributes to the differential expectations held by firms. Prior investment and its associated learning gives the firm experience and insight into the firm's own strengths and weaknesses, as well as the likelihood of success of a project (Bowman & Hurry, 1993). Only through experience and learning will a firm be able to evaluate the importance and merit of intermediate technological advances and, therefore, form more accurate expectations about their commercial return (Cohen & Levinthal, 1990). Failure to invest in absorptive capacity may be both an outcome of failure to invest in development of new core capabilities and may reinforce a firm's inability to develop new core capabilities.

The firm's ability to form accurate expectations about consumer desires, its core capabilities, and the speed with which it can acquire new capabilities are all functions of learning. In sum, investment in learning plays a crucial role in the firm's ability to develop or produce a technology meeting consumer requirements. This leads to the following:

> *Proposition 1: Failure to invest in continuous learning processes will increase the likelihood of technological lockout.*

Very often, however, technologies that appear to meet or exceed consumer expectations are rejected by the market. This phenomenon is particularly likely in markets characterized by network externalities. The industrial organization economics research on network externalities indicates that technology adoption decisions often are driven by the size of the technology's installed base or its availability of complementary goods, rather than its technological superiority or inferiority. I consider these two factors and their self-reinforcing effects next.

Insufficient Installed Base

In industries characterized by network externalities, consumers will be strongly influenced in their adoption decisions by the size of the installed base (the degree to which the technology currently is used by commercial adopters) of a technology (Katz & Shapiro, 1986, 1992).[6] I have already discussed, at some length, network externalities, so I omit an in-depth explanation here. In short, the size of the installed base is directly related to the benefits a consumer derives from using the technology; therefore, other things being equal, a technology with a large installed base is preferable to a technology with a small installed base. Therefore, a small installed base of the technology a firm supports increases the likelihood of that technology being rejected by the market.

> *Proposition 2a: In industries characterized by network externalities, an insufficient installed base will increase the likelihood of technological lockout.*

Several factors may give one technology producer an installed base advantage over others. First, a company that is vertically integrated forward or has strategic alliances with distributors or users of its technology may have an advantage in quickly establishing an installed base of the technology. A firm can diffuse its technology through licensing arrangements and open systems. A firm may also increase the size of the installed base through aggressive advertising. In fact, the firm may be able to influence consumers' *perception* of the existing installed base of the technology (through, for example, "vaporware") and, thus, increase the likelihood that consumers choose that technology and subsequently increase the *actual* installed base. Additionally, as Katz and Shapiro (1986) note, a firm may choose to sponsor the technology through penetration pricing in order to improve the technology's chances of being selected as a dominant design.

[6] It is important to note that installed base does not equal market share unless the firm is the sole provider of a particular technology standard. In many markets the installed base of a technology may be very large, although individual providers of the technology have relatively small market shares. A good example of this is the market for IBM-compatible PCs. Although over 95 percent of the personal computers installed on Fortune 1000 desktops are IBM compatible, no single firm has more than a 14 percent share of the personal computer market.

Timing of entry may influence the size of the installed base because, other things being equal, an early entrant has more time to promote, deploy, and improve its technology. For instance, the technology, when first developed, may cause increasing returns to adoption, thus yielding a rapidly growing installed base. A later entrant not only has less time to deploy its technology prior to selection of a dominant design but may also find that buyers have already adopted an earlier technology and are unwilling to invest in the later entrant's technology (the direct effects of timing are considered later in the article).

> *Proposition 2b: Timing may have a mediated effect on the likelihood of technological lockout by influencing the size of the installed base. Later entry increases the likelihood of having an insufficient installed base, which increases the likelihood of technological lockout.*

Lack of Complementary Goods

Many technologies are not useful or desirable to customers without an associated set of complementary goods (e.g., computers and software, VCRs and videotapes, or copy machines and toner cartridges). Some firms make both a good and its complements (for instance, Kodak produces both cameras and film), whereas others rely on other companies to provide complementary goods or services for their products (e.g., computer manufacturers often rely on other vendors to supply service and software to customers). Firms that do not produce their own complementary goods may find themselves vulnerable to technological lockout because of lack of complementary goods available to consumers. The network externalities research shows that the extent of availability of complementary goods affects a consumer's choice between differing technologies (Choi, 1994; Farrell & Saloner, 1985; Katz & Shapiro, 1986, 1992; Thum, 1994). Therefore, in an industry characterized by network externalities, a firm producing a technology for which there is a lack of complementary goods is likely to find its technology rejected.

For a well-known example of this, consider Sony's introduction of the Beta standard in videorecording. When videocassette recorders first became available, Matsushita offered recorders based on its VHS standard, whereas Sony produced recorders based on its Beta standard. Matsushita diffused its technology through liberal licensing agreements, resulting in rapid production of videotapes based on the VHS standard. Despite the fact that, by many reports, the Beta standard was a superior technology, consumers opted for VHS recorders in order to take advantage of the wide selection of VHS-compatible videotapes. Sony's Beta standard essentially was locked out of the market. More recent examples of this include IBM's Microchannel (a proprietary server architecture that peripheral manufacturers did not support owing to its expense) and the precipitous decline of the Macintosh personal computer.

The size of the installed base and the availability of complementary goods will be highly correlated because the variables have powerful self-reinforcing effects. A technology's installed base will influence the choice of manufacturers of complementary goods. Assuming that there are increasing costs associated with supporting multiple technologies, complementary goods providers face a technology adoption choice similar to that of consumers. Supporting a technology with many users will be more valuable to them than supporting a technology with few users and, thus (with the possible exception of a few niche providers), complementary goods providers are likely to support the technology with the largest installed base. The availability of complementary goods influences, in turn, the technology adoption of consumers, which further increases the installed base. The reciprocal case is also true; a technology with a small installed base is unlikely to attract complementary goods providers, which, in turn, dissuades consumers. A self-perpetuating cycle ensues.

Even in industries not characterized by network externalities, a lack of complementary goods may cripple a firm's technology offering. Producers of complementary goods may find that some design architectures are easier or more profitable to provide complements for than are others. Furthermore, transaction costs may induce complementary goods suppliers to arrange exclusive contractual relationships with a single technology manufacturer (Williamson, 1975). If producing the complementary goods requires specialized assets compatible with only one technology design, the producer bears a risk by committing to the assets. The firms, therefore, may set up contracts or strategic alliances, whereby the production of the complementary good is partially subsidized, or a minimum sales amount is guaranteed, by the sponsor of the technology design. Alternatively, even if production of complementary goods does not require specialized assets, if complementary goods providers are rare, technology sponsors may use exclusivity contracts to preemptively "capture" these providers, thereby securing a scarce resource and possibly a competitive advantage (Barney, 1991; Lieberman & Montgomery, 1988). The major videogames producers (Nintendo, Sony, and Sega) are notable for using this tactic of influencing technology adoption. Exclusive contractual arrangements are set up between the game machine manufacturers (e.g., Nintendo) and games producers (e.g., Acclaim).

If, for a given technology, there is a necessary set of complementary goods required for the technology to be useful or desirable to customers and a firm is unable or poorly suited to produce its own complementary goods, that firm is at the mercy of other complementary goods providers. If complementary goods providers do not support the technology, or the complementary goods produced are not of competitive price or quality, the firm may find its technology locked out of the market.

Proposition 3a: For technologies requiring complementary goods, a lack of complementary goods will increase the likelihood of technological lockout.

Proposition 3b: The strength of the relationship between lack of complementary goods and technological lockout will be increased by the presence of network externalities.

As mentioned before, the timing of entry may influence the size of the installed base. However, this is not the only way that timing influences technology adoption. The timing of entry and its influence on technological lockout is discussed next.

Timing of Entry

In an industry where pressures encouraging adoption of a dominant design exist, the timing of a firm's investment in new technology development may be critical to its likelihood of success. Scholars in both the strategy and marketing strategy fields have done quite a bit of research on the timing of entry. Their research does not reach a consensus on whether being a first mover or second mover is better for a firm's chances of having its technology selected as a dominant design.

Being a first mover may confer the advantages of technological leadership and preemption of scarce assets, and it may allow the firm to exploit buyer switching costs (Lieberman & Montgomery, 1988; Spence, 1981). Furthermore, as discussed earlier, in an industry characterized by increasing returns to adoption, there are powerful advantages to being an early provider: a technology adopted early may rise in market power through self-reinforcing positive feedback mechanisms, culminating in its entrenchment as a dominant design. Intel is an apt example of this. Intel's Ted Hoff invented the first microprocessor in 1971, and in 1975 Bill Gates and Paul Allen showed that the microprocessor could run a version of BASIC (which Gates had written). Gates' BASIC became widely circulated among computer enthusiasts, and as BASIC was adopted and applications developed for it, the applications simultaneously were optimized for Intel's architecture. IBM's adoption of the Intel's 8088 microprocessor in their PC introduction secured Intel's dominant position, and each of Intel's subsequent generations of products has set the market standard (Ferguson & Morris, 1994).

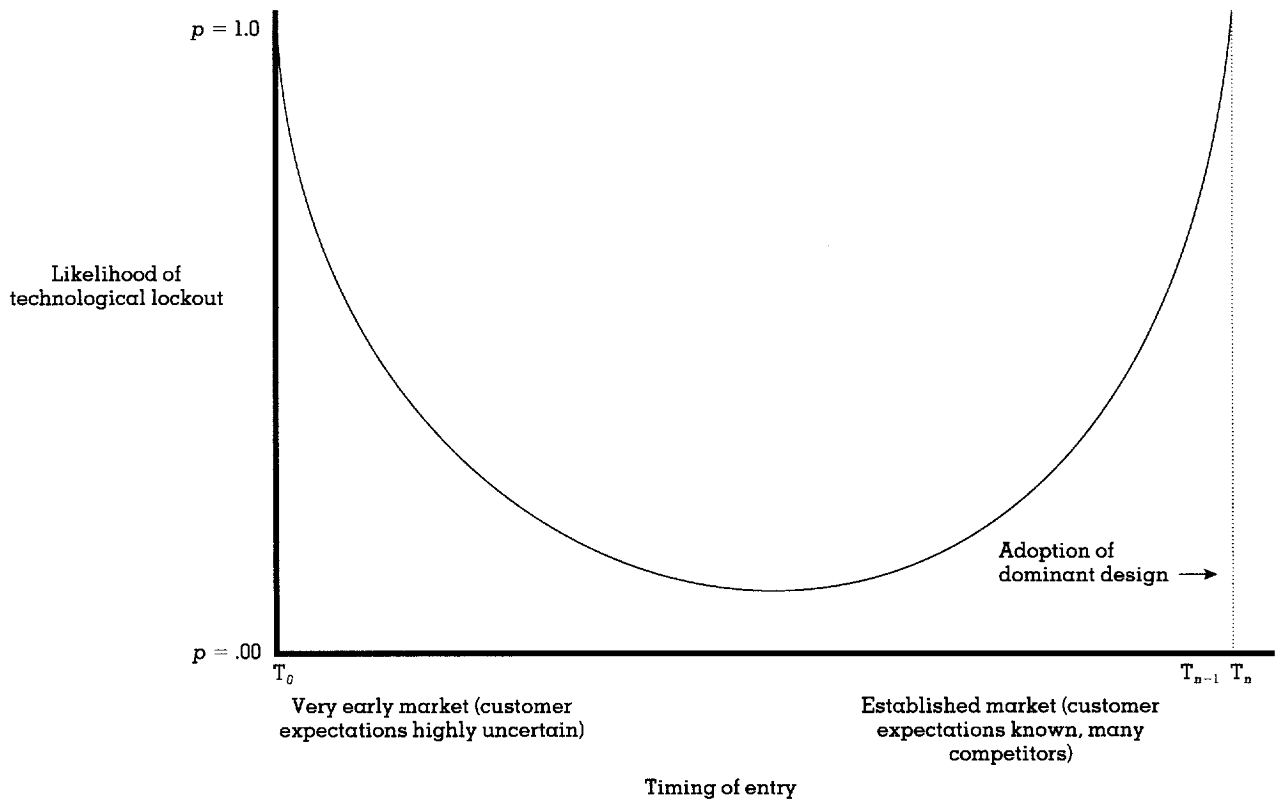
However, arguments also exist for not entering a market too early. A later entrant often can capitalize on the research and development investment of the first mover, can fine tune the product to customer needs as the market becomes more certain, can avoid any mistakes made by the earlier entrant, and can exploit "incumbent inertia" (Lieberman & Montgomery, 1988). For instance, when Kodak introduced the 8-mm videocamera in the late 1980s, the product was rejected by consumers, and Kodak decided to withdraw from the market. Consumers had not yet recognized a need for this product and were unsure of what value it could provide. However, by the early 1990s, consumers had become more comfortable with the concept of 8-mm-videocamera technology, and several competitors (most notably, Sony) were able to enter this market successfully.

It appears, then, that the relationship between timing and technological lockout has several important interactions with the state of the industry and customer expectations. In very early market stages, a technology may be underdeveloped and its fit with customer needs unknown. Furthermore, necessary complementary goods and services may not be developed yet. That technology's likelihood of being adopted as a dominant design is low. Supporting this, Anderson and Tushman found, in their 1990 study, that no technological discontinuity became the dominant standard; in every case some subsequent improvement became the industry benchmark. Over time one would expect the knowledge of the technology and customer expectations to improve (and support goods and services to be developed), thus increasing the likelihood that sponsored technologies will possess a set of attributes meeting consumer demands. However, if the technology proves to be valuable, over time there will also be market entry by competitors, and, if there are pressures for coalescence around a dominant design, a competing technology design may become so entrenched that later technology offerings will have little opportunity to capture market share. These technologies subsequently may be rejected because of an insufficient installed base or because they are behind on the learning curve. This suggests the possibility of a U-shaped relationship between timing of entry and the likelihood of technological lockout (see Figure 2).

> *Proposition 4a: Timing of entry will have a U-shaped relationship with the likelihood of lockout: entering very early or very late will increase the likelihood of technological lockout.*

The deflection point of the curve will depend on the degree of customer awareness and consensus on desired product features, and finding (or influencing) that deflection point will be of utmost importance. Both the deflection point and

FIGURE 2
Timing of Entry and Likelihood of Technological Lockout



the strength of the U-shaped relationship will be moderated by the intensity of network externalities in the industry, barriers to competitive entry, and the margin of improvement the new technology offers over previous technologies competing for the same market.

Network externalities increase the pressure for adoption of a single dominant design, which can shorten the time to standard adoption. This would cause the second half of the U-shaped curve (the increasing portion) to become steeper as the likelihood increases of a competitor's design being adopted as the dominant design. Entry barriers may dampen this effect by slowing competitive entry and, thus, lowering the likelihood of a competitor's technology being adopted as a dominant design prior to the entry of the firm of interest.[7] For instance, some technologies may require extremely large capital investments or scarce resources (such as specially skilled employees), or they may be based on other technologies that are protected by patents, copyrights, or secrecy. In such a situation, fewer competitors may enter the market or may take longer to enter, thus giving the firm more time to establish its own technology as a dominant design.

The degree to which the technology represents an improvement over previous technologies also will have a dampening effect on the first half of the U-shaped curve. That is, when a technology yields a dramatic improvement over previous generations or different technologies that serve similar functions, that technology will more rapidly gain customer acceptance. There will be less ambiguity about the value of the technology and more early adoptions (as well as more support by complementary goods providers); as a consequence, customer expectations should become known sooner, and the firm should be able to successfully enter the market earlier.

Proposition 4b: The strength of the relationship between late entry and technological lockout will be increased by network externalities and low entry barriers.

Proposition 4c: The strength of the relationship between very early entry and technological lockout will be weakened by the degree of improvement the technology offers over previous technologies.

Type II Technological Lockout

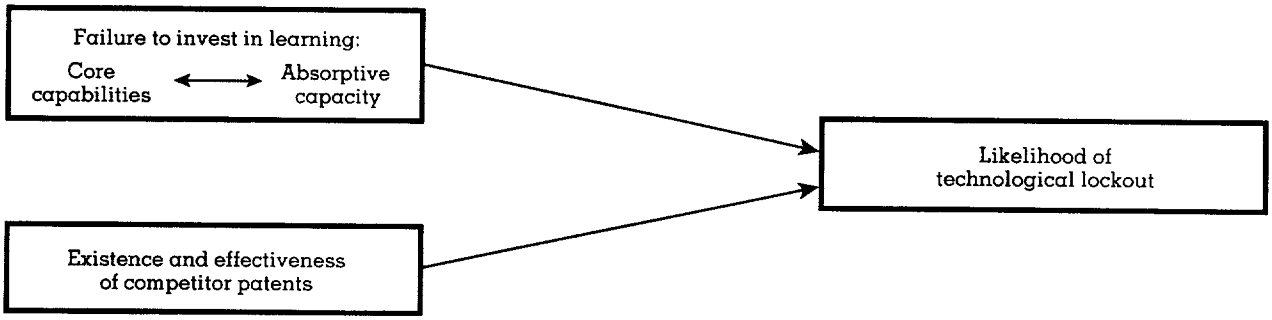
There is an existing dominant design and the firm is unable to (or barred from) producing or selling products conforming to this standard.

In an industry that has an established dominant design, factors that influence technology choice, such as installed base, complementary goods, and timing, become null issues; the technology has been adopted already, so one can assume that the installed base was not insufficient and that complementary goods, if necessary to the technology, are available. Furthermore, once the dominant design is established, timing also becomes less critical. Although there may be some learning or reputation effects associated with being an early entrant, these effects may not be crucial to the success of a firm in producing an already-established dominant design. What, then, would prevent a firm from being able to produce or sell a product conforming to an established dominant design? Patents, copyrights, and other forms of legal protection can prevent a firm from duplicating a proprietary design. However, even when the technology is not protected, a firm may not be able to produce it if it lacks critical capabilities.[8] Firms are more likely to lack these critical capabilities (and the ability to gain these capabilities quickly) if they have not invested in continuous learning (see Figure 3). It is interesting to note that this condition of technological lockout probably is very common yet is rarely casually observed. It often results in a "nonevent," meaning that the firm chooses to do nothing. The

[7] An alternative argument could be made that because there are fewer competitors in the market, the market may be able to coalesce more quickly around a single standard than when many firms with competing technologies vie for the dominant position.

[8] As I discussed at the beginning of the article, there are certainly other idiosyncratic events or attributes that may pose entry barriers to a firm wishing to produce products conforming to the dominant design; however, I limit discussion here to those factors most regularly, and significantly, influencing the outcome.

FIGURE 3
Factors Influencing the Likelihood of Type II Technological Lockout



great majority of lockouts of this form may be identified only by the firms whose market entries were barred.

Existence and Effectiveness of Competitor Patents

When there is an established dominant design in a market, the existence and effectiveness of patents[9] protecting that design increase the likelihood of a nonsponsoring firm being locked out. As Katz and Shapiro (1986) note, Firm B may be able to prevent Firm A from producing a compatible product if Firm B has strong legal property rights to the technology. Furthermore, if a second-generation technology[10] can be introduced in a market only if it is compatible, then Firm B will prefer incompatibility, and if Firm B has strong property rights, the second-generation technology will never be introduced.[11] Firm A is technologically locked out. The following example illustrates this point.

Prior to 1976 Polaroid (the firm that first provided instant photography) monopolized the U.S. instant-photography market. In 1974 Kodak became interested in entering the instant-photography market and began developing its own instant-film technology and cameras. Kodak's entry into the instant-photography market precipitated an increase in instant-camera sales, from 3 million units in 1975 to more than 8 million units in 1976. However, despite this apparent positive impact on the instant-photography market, in 1978 Polaroid sued Kodak for patent infringement. A long court case ensued, and on January 8, 1986, a federal court ordered Kodak to leave the instant-photography business (Mahajan, Sharma, & Buzzell, 1993). Kodak was left with $200 million worth of equipment it could no longer use and had to pay $150 million in cash and certificates to compensate Kodak instant-camera owners because Kodak instant film no longer would be available. On October 12, 1990, Kodak was also ordered to pay Polaroid $909.5 million—marking the largest patent infringement settlement ever awarded to a company (Mahajan, Sharma, & Buzzell, 1993).

It is important to note that not all patents are created equally: the effectiveness of patents varies considerably across industries (Levin, Klevorick, Nelson, & Winter, 1984). For example, in the chemical and pharmaceutical industry, patents are quite powerful tools for preventing imitation (Mansfield, Schwartz, & Wagner, 1981). However, in the electronics industry there are large categories of products and technologies that are not patentable (Cohen & Levin, 1989) and even more categories where patents do little to prevent competitors from "inventing around" the property rights (Lieberman & Mont-

[9] I use the term "patents" here to refer to patents, copyrights, and other forms of legal protection of proprietary technology.

[10] A second generation of technology is a new platform—or family—of products representing a significant improvement over (or change from) the previous platform. For instance, one can view the 3½" disk drive for personal computers as a second generation of technology, following the 5¼" disk technology (although it might be seen as the third or fourth generation, if one expands the market beyond that of personal computers).

[11] This is sometimes mitigated by the use of sophisticated licensing arrangements that enable Firm A to pay Firm B for the right to produce compatible products, but such arrangements raise antitrust concerns because they can amount to a collusive outcome where Firm B pays Firm A to not compete.

gomery, 1988). Therefore, under conditions of an existing dominant design, the ability of firms to lock competitors out of the market with patents is related to both the existence and effectiveness of the patents in protecting the dominant design.

> *Proposition 5: Under conditions of an existing dominant design, the likelihood of technological lockout is positively related to the existence and degree of effectiveness of competitor patents protecting the dominant design.*

Lack of Core Capabilities and Absorptive Capacity

Since core capabilities and absorptive capacity were discussed in-depth earlier in the article, the discussion will not be repeated here. Instead, a brief explanation follows of how failure to invest in learning may prevent a firm from being able to produce products conforming to an established dominant design.

Markets often evolve through different generations of technologies. Frequently, these generations involve quantum (or "discontinuous") technological improvements. Firms that do not continuously invest in learning may fail to anticipate a technological change and may be unable to respond to it quickly.

Smith Corona and Keuffel & Esser are both prime examples of firms that failed to anticipate a major technological change in their markets and lacked the core capabilities to compete in the market once the new dominant design had been established. Both companies also had been market leaders prior to the technological shift, and it may have been this market leadership that made the companies complacent with an aging capability base. Whatever the cause, the impact for both firms was dramatic.

Smith Corona did not foresee the demise of the electronic typewriter until it was too late. The company scrambled to bring a computer to market in 1992 by entering into a joint venture with Acer Inc.; however, the product did not survive the retail personal computer shakeout of that same year, and the venture was terminated. Smith Corona survived another couple of years on sales of its other office products, but by 1995 it had filed for Chapter 11 bankruptcy.

The story of Keuffel & Esser is a similar one. This company obtained the patent rights to Edwin Thatcher's slide rule sometime between 1881 and 1890. During the 1950s and 1960s Keuffel & Esser was the preeminent slide rule maker in the United States, producing 5,000 slide rules a month. But by 1970 inexpensive handheld electronic calculators had relegated the slide rule to collectors' and museum displays. Keuffel & Esser lacked the competencies necessary to produce electronic calculators and went out of business in 1976 (Scuria-Fontana, 1993).

In both of the preceding examples, very well-known firms were locked out of markets because they failed to make the necessary investments in learning to respond to technological change. Undoubtedly, there have been many other firms whose inability to produce an established dominant design was less visible because the firms were not market leaders of a preceding technological generation. Firm failure owing to an inability to produce goods meeting customer expectations in terms of features and quality is commonplace. In cases where the technology is easily imitated or externally acquirable, technological lockout poses less of a threat. However, in industries where the technology is tacit, protected, or embodied in the specialized skills of rare individuals, a firm may find that it does not have the needed capabilities and may not be able to acquire them quickly.

Firms can better their chances of having the necessary core capabilities and/or the absorptive capacity to develop them quickly by investing in continuous learning and technology development. A firm not investing in such skills may be technologically locked out of the market.

> *Proposition 6: Under conditions of an existing dominant design, failure to invest in continuous learning will increase the likelihood of technological lockout.*

DISCUSSION

In this article I develop a model of the forces driving technological lockout—a model having implications both for future technology development and for technology management. It extends the previous work on technology selection and network externalities and poses an argument counter to much of the literature on nonlinear dynamics and complexity theory: although nonergodicity may cause random events to influence technology trajectories, their effects may accrue in an *ordered* manner. Those undertaking future research should attempt to extend this model to ensure its comprehensiveness and explore whether other conditions should be added to the model or whether research or management practice yields other factors that regularly influence the likelihood of lockout. For example, are there more specific industry scenarios conditioning the importance of factors influencing the likelihood of lockout? Are there important technology factors either forward or backward in the distribution chain that have not been identified here? Are there other forces causing a coalescence around a dominant design that have not been examined, and from these forces can we derive other factors influencing the likelihood of technological lockout?

Additionally, scholars should attempt to further develop the strategic implications of technological lockout. One area that has begun to receive increasing attention is project valuation. Net Present Value (NPV) methods usually are inadequate for capturing the strategic importance of a development decision (Azzone, Bertele, & Masella, 1993) or the costs associated with becoming locked out. Many projects that are evaluated with a negative NPV may prove to be profitable in the long run because of later applications of the technology or the learning acquired during the development of the technology. Furthermore, the use of NPV methods requires the firm to provide an estimate of demand for the resulting technology. However, the possibility of technological lockout means that companies may face discontinuous expected demand curves. As Arthur (1989) notes, if a technology yields constant or decreasing returns to adoption, the expected demand for the technology can be modeled and estimated; however, if the technology faces increasing returns to adoption, then random historical events will influence the outcome, so predictability is lost. This may mean that option models, multidimensional scaling models, or possibly even cusp catastrophe models (Oliva, 1991) would be better for evaluating technology development decisions. More researchers should aim to develop and test these ideas, as well as to develop other ways to value development projects that include learning advantages.

The implications of this model should be of great interest to managers. For instance, it is posited that a firm's investment in core capabilities and absorptive capacity will greatly influence its probability of technological lockout and that because much of learning is tacit, it may be a source of persistent asymmetries (and, therefore, a potential source of sustained competitive advantage). This indicates that (1) firms can benefit by having a learning orientation (Senge, 1990a,b); (2) because technology development is a primary source of learning, project selection methods should include the value of the accumulated learning in the assessment of a project; and (3) learning should be encouraged in novel and unfamiliar areas.

Because installed base and complementary goods play major roles in technology selection when an industry is characterized by network externalities, the firm needs to employ marketing, distribution, and pricing tactics that will rapidly deploy the technology, even if this means forfeiting returns for the short term. Protecting the technology with appropriability mechanisms (e.g., patents, secrecy, and so on) will slow the technology's diffusion into the marketplace and increase the risk of having the technology locked out altogether.

IBM's microchannel is an excellent example of this. The firm protected its proprietary server bus architecture and charged very high prices to other manufacturers who wanted to build devices to the microchannel specifications. As a consequence, even though microchannel may have had some technical advantages over standard ISA or PCI bus architectures, hard-drive, videocard, modem, and other manufacturers decided they did not need to support microchannel. Consumers also avoided microchannel machines because the upgrades were too costly. IBM's market share slid, and it eventually gave up manufacturing microchannel machines.

A company can rapidly build the installed base of a technology and encourage or sponsor the availability of complementary goods by diffusing the technology through (1) open systems, (2) interorganizational linkages and bundling arrangements (e.g., Microsoft owes much of its current success to its initial bundling arrangement of MS DOS with IBM's personal computers), and (3) aggressive marketing and promotion.

Managing the timing of entry into the market is a complex matter. If the technology has a clear advantage for consumers, entering the market early may give the entrant a path-dependent advantage that is nearly impossible for competitors to overcome. If, on the other hand, a firm enters a market very early and the advantages of the technology are not very clear to consumers, there is a strong possibility that the technology will receive a tepid welcome. Confounding this risk is the fact that watchful competitors may be able to use the firm's failure to their advantage, refining the technology the firm has introduced to the market and making any corrections necessary to improve the technology's market acceptance. The later entrant may be able to enter at a lower cost because it can capitalize on the research and development of the early firm and use knowledge of the market gained from observing the early entrant's experience.

When the technology is ambiguous or consumer expectations are unclear, it may be in the firm's best interest to wait, while the technology and consumer expectations evolve, and then make a more informed decision about entering. However, a firm must be careful not to wait too long, for as the technological options become better understood, there may be much more competitive entry into the market. If a competitor's offering accrues increasing returns to adoption, it may be difficult for the firm to ever catch up. Furthermore, if there are forces encouraging adoption of a dominant design, a competitor's technology offering may be selected, and if such protection mechanisms as patents are effective in this market, the firm may be locked out.

Alternatively, a firm wishing to enter (or establish) a very new or emerging market can improve its chances of having its technology accepted by investing in consumer education. Rather than marketing only its own product's advantages, the firm can promote the technology category as a whole, demonstrating its usefulness and allowing customers an opportunity to try the technology. If the firm can help customers become more certain about their expectations regarding the technology, the firm can speed up the process by which customers adopt the new technology and increase the advantages of being an early entrant.

In the situations described above, it is assumed that timing of entry is a matter of *choice* for the firm. However, implicit in this assumption is a corollary assumption that the firm is capable of producing the technology at any point in the time horizon under consideration. In order for this to be true, the firm must possess the core capabilities required to produce the technology to consumer expectations, or it must be able to develop them quickly. Furthermore, if the firm intends to make refinements on an earlier entrant's technology and beat the earlier entrant to market with a new version of this technology, that firm must have fast-cycle development processes.

This raises another interesting point: if a firm has fast-cycle development processes, the firm not only has a better chance of being an early entrant but can also use experience gained through customers' reactions to its technology to quickly introduce a refined version of its technology that achieves a closer fit with customer requirements. In essence, a firm with very fast development processes should be able take advantage of both first and second mover advantages. The research on new product development cycle time indicates that development time can be shortened greatly by using (1) parallel development processes (De Meyer & Van Hooland, 1990), (2) cross-functional teams (Rochford & Rudelius, 1992), and (3) strategic alliances (Teece, 1986).

CONCLUSIONS

A major contribution of this research relates to the issue of random versus nonrandom effects in determining which technologies are adopted and which are locked out. It is true that idiosyncratic events, such as government legislation, bundling partnerships, and so on, influence technology adoption. However, if these idiosyncratic events influence technology adoption predominantly by affecting one or more of the factors identified in this research, then the proposed model of technological lockout should have both predictive and explanatory value despite idiosyncratic influences. For instance, CP/M's lockout of the operating system market is often attributed to the fact that Gary Kildall chose not to meet with IBM the day that IBM came to speak with him regarding bundling CP/M with the PC. This was an idiosyncratic event. However, the reason it resulted in CP/M's lockout is that the firm forfeited an opportunity to rapidly gain a huge installed base. Gates' MS DOS gained the installed base instead, and through self-reinforcing feedback mechanisms (including increased availability of complementary goods and learning benefits), quickly rose to be the dominant design. This is a nontrivial conclusion; it means that even though path dependency enables idiosyncratic events to have powerful effects, their effects impact technology selection in an ordered way. Furthermore, since other attributes and actions also effect technology selection in an ordered way, the firm can reclaim some degree of control over the technology selection process. Rather than asking whether firms can influence technology selection, we must ask "how much?"

This leads us to a second major issue addressed by the research here—that is, the interaction and relative importance of external factors (e.g., industry conditions, stage of technology evolution, and certainty of consumer expectations) versus internal factors (such as a firm's attributes and strategy) in driving technology adoption. In the industrial organization economics research, scholars have emphasized the role of the external environment in the technology adoption process: the presence of network externalities, customers' choice of technologies based on installed base and complementary goods, the barriers posed by patents, and so forth. However, this is only a partial explanation of the technology selection and rejection process; the research here extends that explanation by showing how firms can influence the technology selection process through strategic management. A firm that has a greater understanding of the forces driving technology selection, and that effectively manipulates them to its favor, should have a competitive advantage in technology markets.

By combining economics research with the strategic literature on new product development, learning, and methods of diffusing one's technology (through, for instance, open systems, strategic alliances, licensing arrangements, and aggressive marketing), it is shown that the technology adoption process may be strongly influenced by *internal* firm attributes and strategies. The firm's breadth of capabilities, the size of the installed base of its technology, the availability of complementary goods, and its timing of entry are all functions of *strategic choices* made by the firm.

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Melissa A. Schilling is an assistant professor of management policy at the School of Management, Boston University. She received her Ph.D. from the University of Washington. Her primary research interests include the strategic development and management of technology, stakeholder theory, and corporate governance.