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Technological Discontinuities and Complementary Assets: A Longitudinal Study of Industry and Firm Performance

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We suggest that the type of complementary assets (generic versus specialized) needed to commercialize a new technology is critical in determining the industry- and firm-level performance implications of a competence-destroying technological discontinuity. At the industry level, we hypothesize that incumbent industry performance declines if the new technology can be commercialized through generic complementary assets, whereas incumbent industry performance improves if the new technology can be commercialized through specialized complementary assets. At the firm level, we posit that an incumbent firm's financial strength has a stronger positive impact on firm performance in the postdiscontinuity time period if the new technology can be commercialized through generic complementary assets. We hypothesize, however, that an incumbent firm's R&D capability has a stronger positive impact on firm performance in the postdiscontinuity time period if the new technology can be commercialized through specialized complementary assets. Drawing on multi-industry, time series, and panel data over a 26-year period to analyze pre- and postdiscontinuity industry and firm performance, we find broad support for our theoretical model.

Key words: technological discontinuities; complementary assets; incumbent industry and firm performance heterogeneity; time series and panel data analyses

In one of the most influential works in economics during the twentieth century, Joseph Schumpeter (1942) posited that "the process of Creative Destruction is the essential fact about capitalism … it is not [price] competition which counts but the competition from … new technology … competition which strikes not at the margins of profits of existing firms but at their foundations and their very lives" (pp. 83–84). Schumpeter argued that new technologies create new market opportunities while simultaneously damaging or destroying demand in many existing markets. Moreover, incumbent firms often experience great difficulty adapting to the changes brought about by a new technology. When confronted with a technological discontinuity, incumbent firms often succumb to internal inertia and suffer years of severe financial dislocation, or even go out of business (Foster 1986).

Prior empirical research has generated important insights and advanced our understanding of the dynamics of technological change (Christensen 1997, Tripsas 1997, Tushman and Anderson 1986), yet this research has focused primarily on incumbent firms as a group, neglecting to inquire into firm-level heterogeneity. Appreciating firm-level heterogeneity is necessary to more fully understand firm competitive advantage (Barney 1991), especially in highly dynamic environments (Teece et al. 1997, Thomas 1996). To present a more complete picture of a technological discontinuity's impact on incumbent performance, we attempt to generate theory at both the industry and the firm level of analysis.

Herein, we focus on industry- and firm-level performance implications of technological discontinuities that destroy the upstream competencies of incumbents (Tushman and Anderson 1986), but whose impact on the downstream competencies exhibits important variation (Abernathy and Clark 1985). Following Teece (1986), we suggest that the type of complementary assets necessary to commercialize the new technology is likely to be paramount in determining the performance consequences for incumbent firms. We argue that incumbent industry performance declines if the complementary assets necessary to commercialize the new technology are generic (these are commodity-type assets that can be transacted for in the open market). On the flip side, we suggest that incumbent industry performance improves if the complementary assets needed to commercialize the new technology are specialized (these are unique assets that are critical to the commercialization of an innovation).

At the firm level of analysis, we identify an incumbent's financial strength and R&D capability as two factors that are pertinent in determining postdiscontinuity performance differentials. In particular, we hypothesize that an incumbent's financial strength has a stronger positive impact on firm performance if the complementary assets needed to commercialize the new technology are generic. By contrast, we suggest that the impact of an incumbent firm's R&D capability on incumbent firm performance has an opposite effect; accordingly, incumbent R&D capability has a stronger positive impact on incumbent firm performance if the complementary assets needed to commercialize the new technology are specialized.

Taken together, we strive (a) to understand the differential performance impact of a technological discontinuity on incumbent firms as a group through an industry-level analysis, and (b) to account for firm heterogeneity in incumbent performance following a technological discontinuity through a firm-level analysis. To test our hypotheses, we draw a sample of incumbent firms from four industries that have each experienced a technological discontinuity. In each case, we employ time series and panel data covering a 26-year time period to test our hypotheses. The results at both the industry and firm levels of analysis are broadly consistent with our theoretical arguments.

Theory and Hypotheses Development

Technological Discontinuities and Complementary Assets

To focus our analysis, we build on the definition of a technological discontinuity put forth in the seminal work by Tushman and Anderson (1986), where a technological discontinuity is defined as representing "technical advance so significant that no increase in scale, efficiency, or design can make older technologies competitive with the new technology. Product discontinuities are reflected in the emergence of new product classes, or in fundamental product improvements. Process discontinuities are reflected in either process substitution or in process innovations that result in radical improvements in industry-specific dimensions of merit" (p. 441). One of Tushman and Anderson's contributions was to categorize different types of discontinuities based on their impact on the technological competencies of incumbent firms. They suggested that technological discontinuities can be classified as either "*competence-destroying*, [which] require new skills, abilities and knowledge in both the development and production of the product" or "*competence-enhancing*, [which] build on existing know-how within a product class … [and] do not render obsolete skills required to master the old technology" (p. 442, italics in original).

In this study, we focus on competence-destroying technological discontinuities. Our point of departure lies in the assumption that the upstream competencies of incumbent firms are destroyed by the emergence of a new technology. Building on the work by Abernathy and Clark (1985), we argue, however, that the impact of a technological discontinuity on industry and firm performance can only be understood when we take into consideration the links between all competencies necessary to successfully commercialize a new technology. Successful innovation not only requires competencies in upstream R&D, but also in downstream market-related activities. In particular, we argue that the performance implications of a technological discontinuity for incumbents are determined in part by the impact of the discontinuity on downstream, complementary assets needed to commercialize the new technology. Hence, we suggest that the impact of a technological discontinuity on nontechnological competencies is critical in determining incumbent performance.

Teece (1986) highlighted the importance of complementary assets in understanding the performance implications of a new technology when he examined the reason why many innovators were unable to capture the economic rents flowing from their innovations. He argued that the commercialization of an innovation "requires that the know-how in question be utilized in conjunction with other capabilities or assets. Services such as marketing, competitive manufacturing, and after-sales support are almost always needed. These services are obtained from complementary assets, which are specialized" (p. 288). The commercialization of the CAT scanner provides a compelling example: The innovator, EMI, lost to the follower, GE Medical Systems, because of a lack of specialized complementary assets.

In his conceptual framework, Teece (1986, p. 289) differentiated between three different types of complementary assets: generic, specialized, and cospecialized. *Complementary assets* that are *generic* need not be adjusted to the innovation, because they can frequently be contracted for in the market on competitive terms. General purpose manufacturing equipment falls into this category. *Specialized complementary assets* exhibit unilateral dependence between the innovation and the complementary assets, and *cospecialized complementary assets* are characterized by a bilateral dependence. GE Medical Systems's stellar reputation for quality and service in hospital equipment is considered a specialized complementary asset, whereas specialized repair facilities for Mazda's rotary engine would be a cospecialized complementary asset. Because the distinction between unilateral and bilateral dependence of the complementary assets and the innovation in question is not critical to our analysis, we use the term specialized complementary assets to denote both specialized and cospecialized complementary assets. Specialized complementary assets are frequently built over long periods of time, and thus are path dependent and often idiosyncratic (Teece et al. 1997). These resources are generally valuable and difficult to imitate and can therefore be a source of competitive advantage (Barney 1991).

Industry-Level Hypotheses

Competence-destroying technological discontinuities are generally initiated by new entrants; they tend to be favored over incumbents, frequently triggering a Schumpeterian process of creative destruction (Tushman and Anderson 1986). The demise of the incumbent industry appears to be particularly salient if the complementary assets needed to commercialize the new technology are generic. In this scenario, new entrants are able to either build the necessary complementary assets internally or contract for them in the market on competitive terms. Incumbents, often hamstrung by inadequate innovation processes and systems (Dougherty and Hardy 1996), have little of value to offer to new entrants. New entrants, however, have a strong incentive to operate alone in order to capture monopoly rents accruing from the successful commercialization of the new technology (Hill 1992).

Examples of this process are numerous and have been well documented (Foster 1986). For example, the transitions from vacuum tubes to transistors, and then from transistors to semiconductors, were accompanied in each wave by a complete turnover in industry leadership. More recently, the emergence of electronic calculators destroyed the entire set of competencies held by incumbents within the electromechanical paradigm. In particular, electronic calculators devalued both the upstream technological competencies and the downstream complementary competencies of manufacturers of electromechanical calculators (Majumdar 1982). The more reliable electronic calculators did not need to be serviced and could be distributed through general office equipment retailers. Thus, if the commercialization of a competence-destroying technological discontinuity is possible through generic complementary assets, we expect the performance of the incumbent firms as a group to decline.

Hypothesis 1. *Following a competence-destroying technological discontinuity, the performance of the incumbent industry declines if the complementary assets needed to commercialize the new technology are generic.*

Not all technological discontinuities necessarily lead to the decline of incumbents accompanied by the rise of new entrants to dominance. By drawing on examples from the automobile industry, Abernathy and Clark (1985) argued that low transilience innovations—i.e., innovations that only affect either upstream or downstream competencies of incumbents, but not both—will not lead to the displacement of incumbents by new entrants. As emphasized above, Teece (1986) highlighted the importance of complementary assets as a critical factor in determining who benefits from innovation. In illustration, Mitchell (1989) found that the possession of specialized complementary assets enhanced the probability that incumbents in the medical diagnostic imaging industry would enter a newly emerging subfield; in fact, the greater the incumbent's specialized complementary assets, the faster the entry would be. More recently, Tripsas (1997), in her study of the typesetter industry, showed that incumbents may be buffered from the negative effects of technological discontinuities if they possess specialized complementary assets.

A technological discontinuity that destroys upstream competencies of incumbents may simultaneously enhance the value of their downstream complementary assets if the complementary assets necessary to commercialize the new technology are specialized. This effect is particularly pronounced in a regime of weak intellectual property protection because specialized complementary assets may allow incumbents to appropriate innovation rents from new entrants (Teece 1986). Frequently, a specialization-based division of labor occurs, where new entrants focus on the upstream, technological competencies and incumbent firms focus on the downstream, complementary assets. Such a scenario finds its expression in extensive interfirm cooperation between new entrants and incumbents. Some observers have suggested that a competence-destroying technological discontinuity that simultaneously enhances the specialized complementary assets of incumbents may lead to a symbiotic coexistence that may benefit both new entrants and incumbents (Pisano 1991, Rothaermel 2000). Although incumbents and new entrants cooperate to create value, they also simultaneously compete to divide up the value created (Brandenburger and Nalebuff 1996). Here, incumbents who possess specialized complementary assets necessary to commercialize the new technology are frequently in a stronger bargaining position to appropriate the joint value created (Lerner and Merges 1998, Teece 1992).

Thus, we argue that the apparently adverse effect of a competence-destroying technological discontinuity may actually have a positive impact on incumbent industry performance if the complementary assets necessary to commercialize the new technology are specialized. If the technological discontinuity merely devalues R&D and production activities, the challenge faced by incumbent firms is less severe. Moreover, if the marketing and sales activities of incumbents are largely unaffected by the change, the value of these activities may even be enhanced if they are specialized assets, making the incumbents more attractive as alliance partners to new entrants. Put differently, incumbents have something to offer to new entrants—they have specialized complementary assets that can be joined with the assets of new entrants to increase the probability of success for both (Teece 1992). Prior empirical work has demonstrated that specialized complementary assets held by incumbent pharmaceutical firms enabled them to establish alliances with biotechnology firms; this not only aided in adapting to the new technology, but also aided in extracting innovation rents (Rothaermel 2001a). We suggest that in the face of a competence-destroying technological discontinuity, the performance of incumbent firms as a group improves if the incumbents hold complementary assets that are specialized to the commercialization of the new technology, because this enables the incumbents to appropriate innovation rents through allying with new entrants.

HYPOTHESIS 2. *Following a competence-destroying technological discontinuity, the performance of the incumbent industry improves if the complementary assets needed to commercialize the new technology are specialized.*

Firm-Level Hypotheses

Regardless of a technological discontinuity's effects on incumbent firms as a group, we expect there to be significant variation among incumbent firms in terms of their ability to adapt to the new technology. Different firms have different resources and capabilities, and this should lead to a great degree of heterogeneity in the ability of individual firms to adapt and survive in response to a technological discontinuity (Hill and Rothaermel 2003). However, the majority of prior research has focused on the performance of incumbents as a group of firms (Christensen 1997, Tripsas 1997, Tushman and Anderson 1986) rather than as heterogeneous entities in their ability to adapt to a technological discontinuity.

We venture a step in this direction by highlighting firm-level factors and their impact on firm performance in the postdiscontinuity time period. In this attempt, we focus on two firm-level factors as determinants of the adaptive ability of incumbent firms: financial strength and R&D capability. We expect both factors to be relevant for firms experiencing a technological discontinuity because financial strength allows incumbent firms to change strategies quickly through pursuing capital-intensive options such as acquisitions (Sanchez 1995), whereas R&D capability reflects a firm's strength in discovery and innovation (Cohen and Levinthal 1989). Financial strength and R&D capability can thus be viewed as part of a firm's dynamic capabilities, which describe a "firm's ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments" (Teece et al. 1997, p. 516).

Financial Strength. When speed of adaptation to a new technology is critical, incumbent firms can establish alliances and make acquisitions in order to access the technology being created by new entrants. In many alliances the incumbent firm will make a minority investment in the new entrant or commit to a series of milestone payments that are contingent on the new entrant's progress with the technology. In acquisitions, the incumbent will typically pay a significant premium over the preacquisition valuation of the new entrant (Caves 1989). More so in the case of acquisitions than in the case of alliances, an incumbent will not be able to do this unless it has significant financial strength. GE, Microsoft, and Cisco Systems, for example, have all repeatedly leveraged their financial strength to acquire start-ups that had discovered and developed promising new technologies with the potential to devalue the incumbents' upstream, technological competencies.

Clearly, financial strength is important to incumbent adaptation to a technological discontinuity regardless of what type of complementary assets is needed to commercialize the new technology. We expect financial strength to be of greater value to incumbent firms if the commercialization of the new technology relies on generic rather than specialized complementary assets, however. If specialized complementary assets are required to commercialize the new technology, incumbent enterprises can access the new technology through interfirm agreements. Although not without costs, this approach is not as capital intensive as making outright acquisitions. Moreover, the bargaining power inherent in the incumbents' control over specialized complementary assets enables them to enter alliances with new entrants on favorable terms (Lerner and Merges 1998). In contrast, new entrants do not need to collaborate with incumbents if the technology can be commercialized using generic complementary assets, which effectively closes one avenue by which incumbents can acquire the new technology. Put differently, the incumbents have relatively weaker bargaining power if generic complementary assets are used to commercialize the new technology because the new entrants not only are in a position to operate alone, but also have a strong incentive to do so because a significant amount of rents accrue to the owners of complementary assets (Hill 1992, Teece 1986). In such circumstances, an attractive option open to incumbents who recognize the importance of rapidly assimilating the new technology is to take the relatively expensive step of acquiring the technology outright by purchasing new entrants.

HYPOTHESIS 3. *Following a competence-destroying technological discontinuity, an incumbent firm's financial strength has a stronger positive impact on incumbent firm performance if the complementary assets needed to commercialize the new technology are generic.*

R&D Capability. Incumbent firms that are faced with discontinuous technological change must acquire new knowledge to ensure their survival. A competence-destroying technological discontinuity shifts the locus of new knowledge away from internal sources toward external ones (Powell et al. 1996). These external sources tend to be new entrants (Tushman and Anderson 1986). One of the reasons that firms invest in their own R&D, however, is to take advantage of external knowledge (Mowery 1983). When studying firms in the semiconductor industry, for example, Tilton (1971, p. 71) noted that internal R&D "…provided an in-house technical capability that could keep these firms abreast of the latest semiconductor developments and facilitate the assimilation of new technology developed elsewhere."

Ongoing investments in R&D have been shown to create a firm-specific capability (Helfat 1994a) that may enable a firm to value, assimilate, and exploit new knowledge (Cohen and Levinthal 1989). Moreover, prior empirical work has produced evidence that the heterogeneous distribution of firm-specific R&D capabilities tends to persist over time (Helfat 1994b). A firm-level R&D capability should thus be a valuable resource in the face of a technological discontinuity and may contribute to superior firm performance (Peteraf 1993).

We submit that an incumbent's R&D capability is more valuable when specialized complementary assets are required to commercialize the new technology than when generic complementary assets are required. R&D capability provides an incumbent with the ability to better understand and value new technological knowledge; the firm's ability to leverage its understanding and enter into alliances with new entrants will be limited if the incumbents downstream assets are generic, however, and therefore of little interest to new entrants. Put differently, an incumbent's R&D capability is less valuable when the new technology can be commercialized through generic complementary assets.

Alternatively, when the incumbents' downstream assets are specialized, new entrants have an incentive to enter into alliances with incumbents in order to access those assets. However, they are more likely to enter into agreements with incumbents who understand the new technology more fully. This aspect of R&D capability is especially pertinent because multiple new technologies or different versions of the same underlying technology often vie for dominance until a new dominant design emerges (Anderson and Tushman 1990). If an incumbent has only a limited understanding of a new technology due to weak R&D capabilities, its production and marketing of that technology will also tend to be less effective. The successful development and commercialization of new technologies requires close integration between R&D, production, and marketing (Abernathy and Clark 1985). If incumbents lack the R&D capabilities necessary to understand and assimilate new technology, they are going to be less able to leverage their specialized production and marketing assets to commercialize the new technology.

Taken together, R&D capabilities are more valuable when the incumbent firms possess specialized assets than when they possess generic assets. Moreover, for incumbents with specialized assets, the greater their R&D capabilities, the more advantaged they are in dealing with new entrants and the better their postdiscontinuity performance is likely to be.

HYPOTHESIS 4. *Following a competence-destroying technological discontinuity, an incumbent firm's R&D capability has a stronger positive impact on incumbent firm performance if the complementary assets needed to commercialize the new technology are specialized.*

Research Setting

Technological discontinuities are rare events in the evolution of an industry. Tushman and Anderson (1986) studied three industries, from their inceptions over a cumulative 165 years of industry history, and identified eight technological discontinuities. To test our hypotheses, we identified four industries that each experienced one technological discontinuity in a 26-year time frame, for a cumulative 104 years of industry history. Each of the industries was characterized by its well-documented discontinuity and by the availability of longitudinal and homogenous data necessary to conduct industry- and firm-level analyses across multiple industries. Accordingly, we chose the following industries (with the respective discontinuity shown in parentheses): the computer industry (PC), the steel industry (electric arc furnace), the pharmaceutical industry (biotechnology), and the telecommunications industry (wireless telephony).

Tushman and Anderson used drastic advancements in the respective price-performance frontier as the criteria to identify technological discontinuities: "…discontinuities offer sharp price-performance improvements over existing technology" (1986, p. 441). All four of the technologies considered in this study have advanced the price-performance ratio significantly in their respective industries. The PC and wireless telephony have caused exponential performance increases while simultaneously drastically lowering prices. The electric arc furnace has brought exponential performance improvements and significant price cuts because it allows for smaller batches of customized steel. Biotechnology has advanced the performance trajectory tremendously: Scientists are now able to discover and develop new drugs that were previously impossible to create. Furthermore, many drugs that could previously be procured only in small quantities (e.g., insulin) can now be harvested cost effectively in large quantities. Applying the Tushman-Anderson (1986) model of technological change, we submit that all four technologies in this study are considered discontinuities.

More precisely, we argue that when applying the Tushman-Anderson framework to the discontinuities chosen in this study, all four technologies would be classified as competence-destroying for incumbent firms. Tushman and Anderson described competence-destroying technological discontinuities as requiring "new skills, abilities, and knowledge in both development and production of the product" (1986, p. 442). This definition concerns the upstream R&D activities of incumbent firms, and implies that they are devalued or destroyed by such technologies. Prior literature

Table 1 Technological Discontinuities, Complementary Assets, and Incumbent Industry and Firm Performance

Impact on incumbent upstream technological competencies	Type of complementary assets needed to commercialize new technology	Impact on incumbent downstream complementary assets	Effect on incumbent industry performance	Stronger positive effect on incumbent firm performance	Industry examples	Technological discontinuity
Destroying	Generic	Destroying	Decline (H1)	Financial strength (H3)	Computer, steel	PC, electric arc furnace
Destroying	Specialized	Enhancing	Improvement (H2)	R&D capability (H4)	Pharmaceutical, telecommunications	Biotechnology, wireless telephony

has argued that biotechnology and wireless telephony are competence-destroying technological discontinuities (Ehrnberg and Sjöberg 1995, Powell et al. 1996, Stuart et al. 1999). We also place the PC and the electric arc furnace in this category. The upstream R&D activities of incumbents were greatly devalued by the arrival of each of these new technologies: PCs are built using off-the-shelf modular components, electric arc furnaces use scrap steel instead of raw materials as input, biotechnology relies on recombinant DNA technology for drug discovery and development, and wireless telephony is based on radio technology. Accordingly, "a competence-destroying product discontinuity creates a new product class" (e.g., personal computers), and "competence-destroying process discontinuities represent a new way of making a given product" (e.g., steel, pharmaceuticals, and telephone services) (Tushman and Anderson 1986, p. 442). Applying the Tushman-Anderson model, therefore, we submit that all four technologies in this study would be classified as competence-destroying technological discontinuities.

We have argued that the impact of a competence-destroying technological discontinuity on incumbent industry performance depends on the discontinuity's impact on the downstream complementary assets. Here, we suggest that the downstream complementary assets of incumbents in the computer and steel industries were devalued because the new technologies were commercialized through generic assets. The direct sales forces employed in the pre-PC era were of little value to the newly emerging PC manufacturers who focused on direct retailing or the retail channel. Similarly, the steel industry had shifted to independent resellers who were also utilized by the newly emerging mini-mills that employed the new technology.

We posit that the downstream complementary assets of incumbents in the pharmaceutical and telecommunications industries were enhanced because these assets were specialized to the innovation and could be applied without significant additional investments. These specialized assets include regulatory and legal expertise, large sales forces of detail people held by incumbents in the pharmaceutical industry, and the extensive infrastructure of switching networks owned by incumbents in the telecommunications industry. Such specialized complementary assets are built over long periods of time and tend to be capital intensive, so they generally cannot be replicated quickly or contracted for in the market.

Taken together, all four technologies included in this study are competence-destroying with respect to their impact on the upstream competencies, but important variation exists in this group with regard to the impact of the technological discontinuity on the downstream competencies. If the downstream assets needed to commercialize the new technology are generic, the value of the incumbent complementary assets is drastically reduced. If, however, the downstream assets needed to commercialize the new technology are specialized, the value of the incumbent complementary assets is enhanced. Table 1 summarizes the discussion presented above. Below, we briefly describe each technological discontinuity's impact on its respective industry in greater detail.

Computer Industry. Before 1981, the computer industry was dominated by vertically integrated enterprises. These firms manufactured most of the important components in the computer hardware systems, bundled the hardware components with proprietary operating system software and applications software, and sold them via their own sales forces. This era was brought to an end by the arrival of the IBM PC in 1981. In fact, Altari, MITS, and Apple had already validated the existence of a strong consumer user base prior to 1981. In 1979, the arrival of VisiCalc, the first mass application for business users, also helped to establish proof of concept. The 1981 introduction of the IBM PC established the dominant design in the industry, and uncertainty was further reduced as the industry moved from an era of technological ferment to an era of incremental change within the dominant design (Anderson and Tushman 1990). By virtue of its design, the PC signaled a transition from the closed-system architecture of the time to open-system architecture and desktop computing. In the turbulence that followed, large numbers of new enterprises entered at every stage of the value chain as the industry deintegrated (Grove 1996). The center of gravity in the industry shifted rapidly away from incumbent enterprises such as DEC, Wang, Unisys and (ironically) IBM, and toward new entrants such as Compaq, Intel, and Microsoft. The arrival of networking based on client server architecture in the late 1980s and the Internet in the 1990s further accelerated this shift.

The emergence of the PC devalued both the upstream and downstream competencies of incumbents. The upstream R&D and production assets of incumbent enterprises had little relevance to emerging microcomputer makers such as Apple, Compaq, and Dell. Following the lead set by pioneers such as Altari and MITS, the new entrants were able to build computers using off-the-shelf modular components and simple manufacturing processes (for example, Apple started in a garage, and Dell in Michael Dell's dorm room at the University of Texas). The closed-system design philosophy of the incumbents was orthogonal to the mindset required to produce low-cost, open-system personal computers.

Moreover, the downstream marketing and sales assets of incumbents were also of limited value. The incumbents used direct sales forces to sell highly priced machines to the central information systems functions of major corporations, but the new entrants addressed different customer groups. The new entrants sold low-priced machines to retail consumers and departments in corporations. Because they were focusing on different customer groups and using different distribution channels, they did not need the sales, marketing, and service assets of incumbent firms to succeed in an open-systems world. New entrants placed a low value on the downstream assets of incumbents. Instead, they developed their own sales forces, or more commonly used new intermediaries such as the value-added resellers who were springing up to serve this new market. This was possible because the downstream complementary assets needed to commercialize the new technology were generic.

Steel Industry. The technological discontinuity analyzed in the steel industry is the electric arc furnace (EAF). Although it was invented in the 1930s in Austria, EAF technology did not become commercially viable until the late 1960s, when it was incorporated into the first mini-mills. One of the pioneering mini-mill companies, Nucor, began operating its first mini-mill in 1969, but it took several more years to develop the technology to a cost-effective point. Subsequently, mini-mills emerged as a technological discontinuity that took more and more market share away from the incumbent firms that used fully integrated mills.

Traditional steel mills are referred to as integrated mills because their production process begins with raw iron ore and ends with the finished steel product. Mini-mills, by contrast, use scrap steel as their raw material input. By eliminating coke ovens and blast furnaces, mini-mill technology reduces the minimum efficient scale of production by a factor of 10 and the capital cost per ton of capacity by yet another factor of 10 (Adams and Brock 1995). Mini-mill technology was a direct substitute for the primary upstream production assets of integrated mills, and thus devalued them. Moreover, because steel resellers already existed, the mini-mills did not require access to the downstream marketing and sales activities of incumbents in order to reach customers. New entrants such as Nucor or Chaparral relied on generic assets to commercialize the new technology. In the process, the mini-mills increased their market share of all steel sold in the United States to 50% by 2000, up from zero 30 years earlier (Stundza 1997). This gain was made at the expense of the integrated mills, many of which went bankrupt.

Pharmaceutical Industry. In 1973, a research team led by Cohen and Boyer published their breakthrough on recombinant DNA (Cohen et al. 1973), which can be used to engineer organisms that produce valuable human proteins. Many human illnesses are caused by the body's overproduction or underproduction of certain proteins, so the implications of this technology for the pharmaceutical industry were clearly tremendous. As is generally the case with competence-destroying technological discontinuities (Tushman and Anderson 1986), new entrants were the first to develop this potentially powerful new technology. The first biotechnology drug, Humulin, a genetically engineered human insulin, reached the market in 1982. The commercialization of Humulin was based on an alliance between the biotechnology start-up Genentech, which discovered and developed the new drug, and the established pharmaceutical company Eli Lilly, which managed the drug through clinical trials and distributed it through its sales force.

Biotechnology represents a radically different scientific paradigm for discovering and developing new drugs. As such, it devalued the upstream assets of incumbent pharmaceutical firms. For example, the skill loss for a scientist making the transition from the traditional chemical screening paradigm to that of genetic engineering was estimated to exceed 80% (Rothaermel 2001b). Biotechnology does not alter the regulatory process imposed by the Food and Drug Administration, however, nor does it alter the pharmaceutical distribution channels. Proteins still have to go through the same schedule of clinical trials, and they are sold in the same manner to the same customers as the small molecule drugs that are traditionally sold by incumbent pharmaceutical enterprises. Thus, the downstream regulatory and sales assets of incumbent enterprises maintained their value in the face of this technological shift. Because these assets are specialized to the commercialization of biotechnology (Rothaermel 2000), their value was enhanced rather than devalued by the emergence of the new technology. Incumbent pharmaceutical companies were in a position to leverage these specialized complementary assets to commercialize the new biotechnology without any significant additional investments.

Moreover, in contrast to the situation that prevailed in the computer and steel industries, new entrants faced several critical problems. The process of discovering and developing new drugs is time consuming and capital intensive characterized by high levels of risk and uncertainty. It can cost more than $500 million and take up to 15 years to take a new drug from the laboratory through clinical trials to regulatory approval for market introduction. The failure rate is also very high. Some 90% of compounds entering clinical trials fail to make it to the market. Worse still, 7 out of 10 products that make it to the market do not generate sufficient economic returns to cover their cost of capital (Giovannetti and Morrison 2000).

New entrants in the pharmaceutical industry often find themselves capital constrained and unable to obtain the resources required to take promising proteins through clinical trials and to introduce them to the market. Although incumbent upstream competencies were destroyed by the emergence of biotechnology, the incumbents can nevertheless offer both the capital to fund drug discovery and the expertise to commercialize newly developed drugs. Prior empirical work has provided evidence that incumbent pharmaceutical companies (informed investors) possess an informational advantage over capital markets (uninformed investors) in assessing the quality of the research conducted by biotechnology firms, and are thus willing to apply a lower discount rate on capital (Lerner et al. 2003, Majewski 1998).

Moreover, and perhaps more importantly, the pharmaceutical companies possess unique firm-specific competencies, which were developed over time, with respect to certain drug and disease areas. For example, Hoffmann-La Roche holds a strong position in antianxiety drugs, and Lilly dominates the market for insulin. This degree of specialization further enhances the market power of incumbents by significantly reducing the number of potential alliance partners for new entrants. To gain access to these valuable, specialized resources, new entrants are forced to enter alliances with incumbent pharmaceutical enterprises. The incumbents' specialized complementary assets, i.e., their downstream regulatory, marketing, and sales competencies, are enhanced in this scenario. This enables the incumbents to enter alliances on favorable terms, and puts them in a position to capture a significant amount of the economic rents generated from successful new biotechnology products.

Telecommunications Industry. The technological discontinuity we examine in the telecommunications industry is the widespread diffusion and commercialization of cellular telephony that began in the early 1980s. First conceived by Bell Labs in 1947, cellular telephony makes it possible to drastically increase a system's subscriber capacity by using many low-powered transmitters that cover a geographical area, which is in turn divided into smaller cells. Each system has a transmission-switching office that receives calls and in turn sends them through the cells to another cellular phone, or, more frequently, to the local telephone exchange. From there the cellular call is fed into the traditional wireline telephone communication network. Although the technology has been available since the late 1940s, the first cellular mobile telephone system was not introduced until after the breakup of the Bell System monopoly in the early 1980s. Ameritech introduced the first cellular network to Chicago in 1984, followed by a second system in the Baltimore-Washington area. The number of subscribers in the United States grew exponentially, from a base of 91,000 customers in 1984 to roughly 33 million in 1995.

Although cellular services provide users with mobility that wire-based lines cannot offer, the more traditional network has not been left entirely behind by the popularity of the new technology. To route their calls, radio-based cellular systems still rely heavily on the switching networks held by incumbent communications firms. As a result, the growth of the cellular sector has created a symbiotic relationship between the incumbent firms and the new entrants: The incumbent firms need access to the new radio-based technology to develop their own cellular systems, and the newer firms are even more tied (in the short run) to the traditional switching networks dominated by the incumbents (Ehrnberg and Sjöberg 1995). In other words, the technological discontinuity has not made the complementary assets of incumbent firms (i.e., their switching networks) obsolete. Moreover, with respect to the commercialization of wireless telephony, the switching networks are specialized complementary assets because they can be used to transmit cellular phone calls without making any additional investment in these downstream assets.

In theory, the cellular providers can build out their own switching networks and cut the incumbents out of the market altogether. However, this would be both capital- and time-intensive. Building out cell sites is an expensive endeavor due to the capital required for equipment, the cost of acquiring licenses to use the radio spectrum in metropolitan areas, and the cost of acquiring customers (which typically includes giving each customer a "free" cell phone). The capital commitments required to commercialize the new technology are clearly substantial. For example, one of the early pioneers of the technology, McCaw Cellular, had to resort to junk bond financing to raise the requisite capital. Already saddled by high debt, cellular providers have chosen to use the switching networks of incumbent enterprises rather than build their own. Due to the specialized complementary assets held by incumbents, extensive cooperation between new entrants and incumbents emerged in the commercialization of the new technology in the telecommunications industry.

Alliance Intensity

Categorizing the pharmaceutical and telecommunications industries as exhibiting a high degree of cooperation between incumbents and new entrants following technological discontinuous change appears to be validated by the differential industry-level alliance intensity among the four industries in this study. In their respective postdiscontinuity time period, the pharmaceutical companies entered an average of 78 alliances per year, and the telecommunications companies entered an average of 53 alliances per year. By contrast, the computer companies entered an average of only five alliances per year, and the steel companies entered an average of merely six alliances per year. Clearly, the pharmaceutical and telecommunications companies entered significantly more alliances than the computer and steel industries in their respective postdiscontinuity time periods (all differences at $p < 0.001$, while controlling for prediscontinuity alliance intensity).[1] It appears that a significant level of interfirm cooperation between incumbents and new entrants ensues in postdiscontinuity time periods if the commercialization of the new technology relies on specialized complementary assets owned by incumbents. New entrants seem to prefer vertical integration or transacting in the market on competitive terms if the commercialization of the new technology can be accomplished through generic complementary assets.

Research Design

Sample and Data

We focused on incumbent firms in the four industries discussed above. To test our hypotheses, we drew on the Standard & Poor's Compustat and DRI databases, as well as on the Standard & Poor's industry reports from 1972 through 1997. This 26-year time frame reflects the starting and ending date of the industry- and firm-level analyses, which are determined by the availability of homogenous data across all four industries. The Compustat database includes financial, statistical, and market information on publicly held companies. The Standard & Poor's DRI database of economic indicators is a standard database for economic research and serves as the source for relevant macroeconomic data. At the industry level, we used quarterly incumbent industry performance data to ensure sufficient observations in constructing the time series. At the firm level, we obtained annual observations to set up pooled time-series, cross-sectional panels of data. The majority of empirical work in strategic management relies on a cross-section of data rather than on longitudinal panel data, and does not allow, therefore, for causal inferences (Hitt et al. 1998). Longitudinal panel data are considered a superior alternative because they allow the researcher (1) to control for the initial values of the dependent variable, (2) to recognize time lags, and (3) to draw on a larger sample, thus reducing the threat of collinearity among independent variables (Hsiao 1986).

Measures

Industry-Level Measures. Incumbent industry performance, proxied by industry return on equity (ROE) and return on assets (ROA), is the dependent variable to test the industry-level hypotheses. We examined time series of quarterly industry ROE and ROA as measures of overall industry performance in each of the four industries.[2] We controlled for seasonal, industry, and macroeconomic effects. Industry concentration tends to change over time as incumbents merge or exit the industry, which in turn affects overall industry performance. Thus, we controlled for industry concentration through the inclusion of the Herfindahl-Hirschman Index (HHI) time series. The HHI equals the sum of the squared market shares of each incumbent firm in the industry for the respective time period. We employed the growth rate of real U.S. gross domestic product (GDP) to control for macroeconomic effects such as business cycles. To control for systematic performance differences over the four quarters of the year, we included dichotomous quarter dummy variables, with the fourth quarter being the reference quarter.

Firm-Level Measures. Incumbent firm performance, measured as incumbent firm ROE and ROA, is the dependent variable to test the firm-level hypotheses. An incumbent firm's financial strength is measured by the sum of its cash and all securities readily convertible to cash as listed in the current assets section of the balance sheet. This measure of financial strength can be interpreted as a firm's free cash flow (Jensen 1986). Free cash flow is cash flow in excess of that which is required to fund all investment projects that have a positive net present value when discounted at the relevant cost of capital. Because free cash flow by definition cannot be profitably reinvested within the company, it can be considered a proxy for financial strength. We proxied an incumbent firm's R&D capability by its R&D expenditures (Helfat 1997), which are outlays for R&D as listed in the annual income statements. We lagged both variables by one year to compensate for a potential simultaneity bias.

The firm-level dependent variables *ROE* and *ROA* are sensitive to a firm's capital structure as measured by its debt-to-equity ratio. Ceteris paribus, a firm with a higher debt-to-equity ratio must achieve a higher return to compensate its stockholders for the increased risk associated with higher debt (Scherer and Ross 1990).

Thus, we included the ratio of debt-equity in the regression models to control for changes in a firm's capital structure over time as it adjusts its preference for debt versus equity. In parallel with the industry-level analysis, we controlled for industry concentration (HHI) and macroeconomic effects (GDP growth rate) that could potentially influence incumbent firm performance.[3]

We proposed that incumbent firm performance following a technological discontinuity be a function of an incumbent firm's financial strength and R&D capability. An explicit control for time effects was indicated to test the firm-level hypotheses because each industry experienced its technological discontinuity at a different time (Kmenta 1986). To accomplish this, we split the independent variables financial strength and R&D capability into two respective time series: one set of variables representing financial strength and R&D capability prior to the industry-specific technological discontinuity, and the other set of variables representing financial strength and R&D capability in the postdiscontinuity time period. This approach allowed us to isolate the impact of financial strength and R&D capability on incumbent firm performance in the postdiscontinuity time period, while accounting for financial strength and R&D capability in the prediscontinuity time period. We obtained the exact dates of the respective technological discontinuity in each industry from the industry-level analysis.

Estimation Techniques

Industry-Level Methods. The industry-level hypotheses imply that each incumbent industry performance time series should exhibit a statistically significant structural break sometime after the emergence of the technological discontinuity. A structural break in a univariate time series indicates a significant shift in the global trend of a time series. In particular, Hypothesis 1 suggests that incumbent industry performance should decline after the emergence of a technological discontinuity if the complementary assets needed to commercialize the new technology are generic. Because Hypothesis 1 predicts an overall decline in the performance of incumbent firms following a discontinuity, the sign of the indicator variable representing the structural break date is expected to be negative. Conversely, Hypothesis 2 posits that incumbent industry performance should improve after the emergence of a technological discontinuity if the complementary assets needed to commercialize the new technology are specialized. Because Hypothesis 2 predicts an overall improvement in the industry performance of incumbent firms following a discontinuity, the sign of the indicator variable for the structural break date is expected to be positive.

To test for structural breaks in univariate time series, we built on the method used by Ben-David and Papell (1995) and Rothaermel (2001a). We applied the following regression model to each of the industry-level time series, assuming a deterministic trending process:

$$y_t = \alpha + \beta t + \delta DT_t + \phi HHI_t + \gamma gdp_{Yt} + \lambda\ quarter_{it} + \mu_t, \tag{1}$$

where y_t represents incumbent industry performance, t is a time trend, and DT_t is an indicator variable representing the break date in the univariate time series, where $DT_t = t - T_B$ if $t > T_B$, 0 otherwise. The Herfindahl-Hirschman Index (HHI_t) controls for industry concentration, and the GDP growth rate (gdp_{Yt}) controls for macroeconomic effects. The variable $quarter_{it}$ denotes the controls for seasonality. We included a time trend to capture secular movements in the dependent variable. Inserting a time trend is useful because it addresses concerns that underlying trends could potentially bias our inference by introducing a simultaneity bias in the relationship between the dependent variable and the main regressor of interest (indicator variable for break date). The null hypothesis states that $\delta = 0$, meaning that incumbent industry performance y_t is governed by a deterministically trending process without an exogenous shock leading to a structural shift in the time trend. The research hypothesis states that $\delta \neq 0$, meaning that y_t is trend stationary with a one-time break in the deterministic trend function that should occur sometime after the introduction of the new technology. We identified the exact year of a structural break in the univariate time series by applying a maximum Chow test to the indicator variable *break date* (Quandt 1960, Vogelsang 1997).[4]

Firm-Level Methods. To test the firm-level hypotheses, we applied a seemingly unrelated regression (SUR) model, sometimes referred to as Park's estimator (Park 1967). A SUR estimation technique is indicated because all firms in the research sample are participating in the same global economic conditions during each time period, creating possible contemporaneous correlation between and among firms (Greene 1997). The SUR model is estimated using a generalized least square estimation procedure that corrects for both cross-sectional heteroscedasticity and contemporaneous correlation (Beck and Katz 1995). In the same fashion as Henderson and Cockburn (1996) and Helfat (1997), we included firm-fixed effects in the SUR model to account for unobserved, firm-idiosyncratic differences. This allows us to isolate the impact of financial strength and R&D capability on firm performance, while accounting for the impact of other, unobserved firm-specific factors. Including firm-fixed effects also eliminates a potential bias in the regression coefficients in the event that any of the unspecified firm effects are correlated with firm financial strength and R&D capability as well

Table 2 Descriptive Statistics and Correlation Matrix

	Mean	Std. dev.	1.	2.	3.	4.	5.	6.	7.	8.
1. Return on equity	18.36	17.90								
2. Return on assets	7.61	5.03	0.69							
3. Financial strength prediscontinuity	380.54	1,656.60	0.19	0.08						
4. Financial strength postdiscontinuity	777.10	1,356.73	0.62	0.09	0.13					
5. R&D capability prediscontinuity	140.73	629.84	0.19	0.02	0.18	0.10				
6. R&D capability postdiscontinuity	609.70	1,593.26	0.70	0.02	0.08	0.53	0.07			
7. Firm capital structure	0.48	0.63	0.10	0.29	0.03	0.06	0.29	0.04		
8. Industry concentration HHI	4,379.33	1,945.25	0.37	0.52	0.21	0.04	0.52	0.14	0.17	
9. GDP growth rate	2.89	2.22	0.01	0.06	0.04	0.09	0.06	0.06	0.07	0.03

Note. $N = 566$.

as with other regressors (Hausman and Taylor 1981). Applying the seemingly unrelated regression model to test the firm-level hypotheses results in the form

$$\begin{bmatrix} Y_{1t} \\ Y_{2t} \\ \vdots \\ Y_{nt} \end{bmatrix} = \begin{bmatrix} i_{1t} & 0 & \cdots & 0 \\ 0 & i_{2t} & \cdots & 0 \\ & & \vdots & \\ 0 & 0 & \cdots & i_{nt} \end{bmatrix} \begin{bmatrix} \alpha_{1t} \\ \alpha_{2t} \\ \vdots \\ \alpha_{nt} \end{bmatrix} + \begin{bmatrix} X_{1t} & 0 & \cdots & 0 \\ 0 & X_{2t} & \cdots & 0 \\ \vdots & & \vdots & \\ 0 & 0 & \cdots & X_{nt} \end{bmatrix} \begin{bmatrix} \beta_{1t} \\ \beta_{2t} \\ \vdots \\ \beta_{nt} \end{bmatrix} + \begin{bmatrix} C_{1t} & 0 & \cdots & 0 \\ 0 & C_{2t} & \cdots & 0 \\ \vdots & & \vdots & \\ 0 & 0 & \cdots & C_{nt} \end{bmatrix} \begin{bmatrix} \gamma_{1t} \\ \gamma_{2t} \\ \vdots \\ \gamma_{nt} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \vdots \\ \varepsilon_{nt} \end{bmatrix}, \quad (2)$$

where Y_{it} represents firm performance, α_{it} represents firm-fixed effects, and X_{it} represents the independent variables financial strength and R&D capability in the postdiscontinuity time period. The matrix C_{it} represents the control variables for financial strength and R&D capability in the prediscontinuity time period, as well as the controls for capital structure, industry concentration, and macroeconomic effects.

Hypothesis 3 suggests that an incumbent financial strength has a stronger positive impact on incumbent firm performance if the complementary assets needed to commercialize the new technology are generic. By contrast, Hypothesis 4 suggests that an incumbent R&D capability has a stronger positive impact on incumbent firm performance if the complementary assets needed to commercialize the new technology are specialized. One of the benefits of the SUR regression technique is that it allows us to test these contingency hypotheses because SUR estimates an individual coefficient for each firm-level observation.

At the same time, SUR estimation indicates that three different Wald-type tests need to be applied to the individual firm-level coefficients to analyze Hypotheses 3 and 4 (Kmenta 1986). Each of these tests is applied to the fully specified model including all explanatory and control variables. The first test specifies that the joint impact of the coefficients for firm financial strength and R&D capability need to be significant. The second test specifies that the average individual impact of the coefficients for financial strength and R&D capability needs to be significant. The third test evaluates the difference of the average individual coefficient impact across both contexts (generic and specialized complementary assets), and requires that the difference be positive and significant for financial strength when subtracting the scores obtained for the coefficients in the generic and specialized contexts. The same requirement holds true for R&D capability when subtracting the scores obtained for the coefficients in the specialized and generic contexts.

Results

Table 2 depicts the descriptive statistics and bivariate correlation matrix. The bivariate correlations suggest that the impact of an incumbent firm's financial strength and R&D capability is stronger in predicting firm performance in the postdiscontinuity time period than it is in the prediscontinuity time period, at least when measuring firm performance in terms of ROE. This provides some preliminary evidence for the relevance of these two variables for incumbent performance when facing a competence-destroying technological discontinuity. Moreover, the correlations between firm financial strength and R&D capability in both the pre- and post-discontinuity time periods reflect discriminant validity because they are well below the conventional cut-off point of 0.70 (Cohen and Cohen 1983), albeit an increase in their correlation from the pre- to the postdiscontinuity time period is noticeable.

Table 3 Industry-Level Results

Industry	DV	Break date	Intercept	Time trend t	Indicator variable *break date*	Control variable HHI_t	Control variable gdp_{Yt}	Control variable *Quarter 1*	Control variable *Quarter 2*	Control variable *Quarter 3*	Adj. R^2	F-stat.
Computer	*ROE*	1983	−0.78	0.06***	−0.89***	0.01*	−0.05	−2.25***	−1.54***	−2.50***	0.60	21.40***
			(2.09)	(0.01)	(0.09)	(5.09E-4)	(0.16)	(0.52)	(0.46)	(0.54)		
Computer	*ROA*	1983	−1.15†	0.03***	−0.38***	7.15E-4***	0.07	−0.84***	−0.79***	−0.92***	0.74	34.40***
			(0.73)	(0.01)	(0.04)	(2.00E-4)	(0.06)	(0.18)	(0.16)	(0.19)		
Steel	*ROE*	1981	3.11	−0.04†	−1.54***	−3.47E-4	−0.21	0.15	1.59*	0.02	0.66	13.76***
			(3.58)	(0.03)	(0.37)	(0.01)	(0.31)	(0.90)	(0.91)	(0.92)		
Steel	*ROA*	1981	0.18	−0.02†	−0.23*	1.79E-4*	0.06	0.11	0.30	−0.02	0.39	5.27***
			(1.02)	(0.01)	(0.10)	(3.60E-4)	(0.10)	(0.26)	(0.27)	(0.27)		
Pharmaceutical	*ROE*	1986	−1.13	0.02***	0.38***	0.01***	0.01	−0.06	0.25	−0.44*	0.73	36.43***
			(1.22)	(0.01)	(0.05)	(0.01)	(0.08)	(0.22)	(0.23)	(0.22)		
Pharmaceutical	*ROA*	1985	2.47***	−0.01	0.11***	−3.93E-4	−0.01	0.63***	0.48***	0.47***	0.68	21.55***
			(0.42)	(0.01)	(0.02)	(3.47E-4)	(0.03)	(0.08)	(0.08)	(0.08)		
Telecommunications	*ROE*	1985	3.28***	−9.08E-4	0.26***	−2.05E-4	−0.03	0.39*	0.61***	0.47**	0.67	26.19***
			(0.76)	(0.01)	(0.04)	(2.13E-4)	(0.06)	(0.20)	(0.18)	(0.21)		
Telecommunications	*ROA*	1988	9.12	−0.14	0.34†	2.66E-6	−0.01	annual data	annual data	annual data	0.10	1.58†
			(8.64)	(0.20)	(0.24)	(3.19E-4)	(0.13)					

† $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Standard errors are in parentheses.

Industry-Level Results. Table 3 depicts the industry-level results. In all four industries, we observe statistically significant breaks in the incumbent industry performance time series after the introduction of the respective technological discontinuity. Hypothesis 1 states that, following a competence-destroying technological discontinuity, the performance of incumbent firms declines if the complementary assets needed to commercialize the new technology are generic. The qualitative data presented in the research setting indicate that the PC in the computer industry and the electric arc furnace in the steel industry were technological discontinuities that devalued the upstream competencies of incumbent firms, and whose commercialization was possible through generic assets. As predicted in Hypothesis 1, we would expect a decline in the incumbent industry performance in the postdiscontinuity time period following the emergence of the PC or the EAF. The empirical results indicate that 1983 marks the structural break in the performance time series for the computer industry for both the ROE ($p < 0.001$) and the ROA ($p < 0.001$) models. As expected, the sign of the *break date* variable is negative in both models, indicating a decline in overall computer industry performance. Similarly, 1981 marks the structural break in the performance time series for the steel industry for both the ROE ($p < 0.001$) and the ROA time series ($p < 0.05$), and the sign of the *break date* variable is negative in both cases, indicating a decline in overall steel industry performance. As anticipated, both the computer and steel industries experienced a significant decline in incumbent industry performance after the emergence of the respective technological discontinuities. This result provides support for Hypothesis 1.

Hypothesis 2 suggests that, following a competence-destroying technological discontinuity, the performance of incumbent firms improves if the complementary assets needed to commercialize the new technology are specialized. Above, we identified biotechnology in the pharmaceutical industry and wireless telephony in the telecommunications industry as technological discontinuities that devalued the upstream competencies of incumbent firms. They also simultaneously enhanced their downstream competencies because the commercialization of these new technologies depended on specialized assets. As predicted by Hypothesis 2, we would expect an improvement in incumbent industry performance in the postdiscontinuity time period.

Our empirical results show that the structural break in the pharmaceutical industry occurs in 1986 in the ROE time series ($p < 0.001$), and in 1985 in the ROA time series ($p < 0.001$). As expected, the sign of the *break date* variable is positive in both regression models, indicating an improvement in overall pharmaceutical industry performance. In the telecommunications industry, the break date occurs in 1985 based on the ROE series ($p < 0.001$) and in 1988 based on the ROA series ($p < 0.10$).[5] As anticipated, the sign of the *break date* variable is positive in both regression models, indicating an improvement in overall telecommunications industry performance. Consistent with Hypothesis 2, we find that both the pharmaceutical and the telecommunications industries experienced a significant improvement in incumbent industry performance after the emergence of the respective technological discontinuity. In summary, our industry-level hypotheses are supported by the fact that the indicator variables for the respective break dates yielded the predicted signs, and that the structural breaks in industry performance occurred after the successful commercialization of the new technology in every case.

Firm-Level Results. Table 4 presents the firm-level regression results. In parallel to the industry analysis, we applied both *ROE* and *ROA* as dependent variables. Firm-fixed effects and the variables of interest, financial strength, and R&D capability are estimated individually for each firm, and the control variables (firm capital structure, industry concentration, and GPD growth rate) are estimated across all firms.

Models 1 and 3 depict the respective baseline models. Models 2 and 4, each of which represents significant improvements over the respective baseline model ($p < 0.001$), depict the fully specified models. Hypothesis 3 posits that, following a competence-destroying technological discontinuity, financial strength has a stronger positive impact on incumbent firm performance if the complementary assets needed to commercialize the new technology are generic. When applying *ROE* as the dependent variable (Model 2), all three separate tests provide support for this hypothesis ($p < 0.001$ in all cases). When using *ROA* as the dependent variable (Model 4), we find significance for Test 1 ($p < 0.001$), but fail to find support for the more stringent Tests 2 and 3. Taken together, we find partial support for the notion that an incumbent's financial strengths has a stronger positive impact on firm performance if the complementary assets needed to commercialize a competence-destroying technology are generic.

Hypothesis 4 states that, following a competence-destroying technological discontinuity, incumbent R&D capability has stronger positive impact on incumbent firm performance if the complementary assets needed to commercialize the new technology are specialized. When applying *ROE* as the dependent variable (Model 2), all three separate tests provide support for this hypothesis (Tests 1 and 2 at $p < 0.001$, Test 3 at <0.01). We also find support for this hypothesis when applying *ROA* as the dependent variable (Model 4, Test 1 at $p < 0.001$, Test 2 at $p < 0.10$, and Test 3 <0.001). Thus, we demonstrate support for the hypothesis that an incumbent's R&D capability has a stronger positive impact on firm

Table 4 Firm-Level Results

	Dependent variable *ROE*				Dependent variable *ROA*			
Controls	Model 1 base	Model 2			Model 3 base	Model 4		
Firm-fixed effects	Significant		Significant		Significant		Significant	
Financial strength (prediscontinuity)	Included		Included		Included		Included	
R&D capability (prediscontinuity)	Included		Included		Included		Included	
Firm capital structure	4.71*** (0.27)		4.97*** (0.51)		−0.68*** (0.04)		−0.48*** (0.11)	
Industry concentration HHI	−5.46E-3*** (3.67E-4)		−6.85E-4 (6.10E-4)		−1.46E-3*** (8.59E-5)		−3.19E-4 (2.67E-4)	
GDP growth rate	0.08† (0.05)		0.06† (0.04)		0.09*** (0.01)		0.06*** (0.02)	
Independent variables		Test 1: Joint impact	Test 2: Average impact	Test 3: Difference in average impact		Test 1: Joint impact	Test 2: Average impact	Test 3: Difference in average impact
Financial strength (H3) (postdiscontinuity)		69.30***	0.02*** (2.96E-3)	0.03*** (1.42E-3)		11.48***	9.55E-4 (6.07E-4)	−1.06E-3 (2.90E-4)
R&D capability (H4) (postdiscontinuity)		18.03***	0.18*** (0.04)	1.27** (0.07)		10.77**	0.01† (4.87E-3)	0.11*** (5.63E-3)
Chi-Square	450.65***		10,685.42***		724.22***		3,714.77***	
Improvement over base			6,375.28***				2,016.49***	
Adjusted R^2	0.32		0.56		0.55		0.67	

† $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Standard errors in parentheses. Test 1 displays F statistics.

performance if the complementary assets needed to commercialize the new technology are specialized.

We conducted several robustness checks. First, we assessed a potential specification bias arising from unobserved heterogeneity through inclusion of the by one year lagged dependent variables on the right-hand side of the regression models. Second, we tested for potential serial correlation. The results were consistent, and thus reveal neither a specification bias nor serial correlation.

Discussion

We studied incumbent industry and firm performance in four industries that each experienced a competence-destroying technological discontinuity (Tushman and Anderson 1986). We hypothesized that the impact on industry performance depended on the type of nontechnological, complementary assets necessary to commercialize the new technology. In line with our predictions, we found that incumbent industry performance declined if the new technology could be commercialized through generic assets, but that incumbent industry performance improved if the new technology could be commercialized through specialized assets.

At the firm level, we posited that an incumbent firm's financial strength has a stronger positive impact on incumbent firm performance in the postdiscontinuity time period if the new technology can be commercialized through generic complementary assets. By contrast, we hypothesized that an incumbent firm's R&D capability has a stronger positive impact on incumbent firm performance in the postdiscontinuity time period if the new technology can be commercialized through specialized complementary assets. Based on an analysis of longitudinal data across four industries, we found broad support for the firm-level hypotheses.

These findings tie in with Abernathy and Clark's (1985) concept of low transilience innovation, which suggests that incumbent firms can benefit from technological discontinuities if their market-related competencies remain unchanged. Our results also reinforce the necessity of comprehensively analyzing an innovation's impact on incumbent enterprises, including all links between different firm competencies. Here, we focus on the link between technological and nontechnological competencies. In their study of the semiconductor photographic alignment equipment industry, Henderson and Clark (1990) showed that seemingly minor technological advances can have severe consequences for incumbents if the new technology changes the architecture in which the components are integrated. Although we focus on major rather than minor advances in technology, our results resonate with Henderson and Clark's (1990) finding that the consequences of technological change can only be accounted for when considering its impact on the entire set of incumbent competencies.

In addition, we focus on an empirical investigation of the innovation framework advanced by Teece (1986). In agreement with his conceptual model, we find support for the importance of complementary assets in determining who benefits from a new technology. Prior empirical work has pointed to complementary assets in explaining firm entry into newly emerging technological subfields (Mitchell 1989), the continued survival of incumbent firms facing technological discontinuities (Tripsas 1997), or extensive interfirm cooperation between incumbents and new entrants (Rothaermel 2001a); we go beyond these single industry studies, however, and advance a more comprehensive contingency model. By studying four different industries longitudinally, covering both pre- and postdiscontinuity time periods, we provide evidence for the notion that incumbent industry performance declines if the new technology can be commercialized through generic complementary assets, but that it improves if the new technology can be commercialized through specialized complementary assets.

Prior research has generally treated the performance of incumbents as a group of firms (Christensen 1997, Rothaermel 2000, Tripsas 1997, Tushman and Anderson 1986) rather than heterogeneous entities in their ability to adapt to technological change. In line with the resource-based view (Barney 1991), we suggest that firms are endowed with heterogeneously distributed resources, which should impact their performance following a technological discontinuity. In an attempt to shed some light on expected firm-level heterogeneity, we focus on firm financial strength and R&D capability and find that these two firm-level factors are important in explaining firm differential performance in the postdiscontinuity time period. These resources can be considered part of what Teece et al. (1997) understand as dynamic capabilities; they describe a firm's "capacity to renew competencies as to achieve congruence with the changing business environment" (1997, p. 515).

Methodologically, this study differs in several aspects from prior work. We employ a longitudinal, multiindustry, multilevel, quantitative approach, whereas most prior studies in this line of research are single-industry studies (King and Tucci 2002; Mitchell 1989; Rothaermel 2001a, b; Tripsas 1997) that often rely exclusively on qualitative case histories (Abernathy and Clark 1985, Christensen 1997, Dougherty and Hardy 1996, Henderson and Clark 1990, Rothaermel 2000) or nonparametric estimations (Tushman and Anderson 1986, Anderson and Tushman 1990). Although we draw on some qualitative data when analyzing our research setting, the quantitative methodologies employed at the industry and firm level of analysis may aid future researchers in moving beyond single-industry and case studies. Such a shift in research methodology should improve the generalizability of the research conducted on the dynamics of technological change and its impact on industry and firm performance.

Limitations and Future Research

It is important to note that the impact of technological discontinuities on an industry cannot be determined prior to the occurrence of the new technology. Tushman and Anderson (1986, p. 443) emphasized that technological discontinuities can only be recognized ex post: "technological discontinuities... are only known in retrospect." Thus, one cannot determine prior to the discovery of a discontinuous technological innovation whether the complementary assets needed to commercialize the new technology are generic or specialized in nature. It follows that one cannot determine ex ante how a technological discontinuity that has yet to be discovered will affect industry and firm performance. Once a new technology has been discovered, however, one can ask: How will this affect the existing industry environment, and thus affect incumbent industry and firm performance? Here, it is important that future research more fully appreciates the contingencies inherent in different stages of technological discovery: theoretical feasibility, technical feasibility, and prototype. In our analysis, we focus on discoveries that have moved beyond theoretical feasibility; however, a more fine-grained analysis is certainly warranted.

We believe that our theorizing efforts will aid in predicting how a newly discovered technology will affect the evolution of an industry environment before that impact has become apparent. Thus, one might have predicted when recombinant DNA technology was pioneered in 1973 that biotechnology would change the upstream processes of drug discovery and production while leaving downstream, complementary assets such as marketing and sales activities largely unchanged. However, this change did not become obvious for at least a decade, as illustrated by the abortive attempts of many biotechnology companies to establish themselves as fully integrated pharmaceutical companies.

Similar to prior empirical work (Mitchell 1989, Tripsas 1997), we rely on a qualitative approach to understanding a technological discontinuity's impact on incumbent technological competencies and complementary assets. However, we suggest that future research should move beyond such qualitative categorizations and attempt to employ more objective, quantitative measures when analyzing the impact of a discontinuity on incumbent upstream and downstream competencies.

It is also valuable to note that out of the four technological discontinuities, only one of them (PC) is a product discontinuity; the remaining three (EAF, biotechnology, and wireless telephony) are process discontinuities. Moreover, one could argue that the underlying technological discontinuity in the computer industry was not the PC per se, but was, rather, Intel's development of the first microprocessor in 1971. Although the microprocessor had no obvious market potential when it was first invented, it dramatically changed the computing industry when it was embedded in the PC (Freiberger and Swaine 2000). This opens the door for future research on two fronts: First, the findings, in particular for product discontinuities, need to be generalizable. Second, the issue of modularity needs further attention (Schilling 2000). Here, we will need a better understanding of modular innovation (Henderson and Clark 1990), which includes component discontinuities such as the microprocessor, and their impact on incumbent performance.

One limitation of this study concerns alternative explanations for the structural breaks observed in the incumbent industry performance time series. The results for the computer industry appear to be robust. The emergence and diffusion of the PC, in combination with its greatly improved performance over time, have indeed led many (corporate) customers to switch from mainframe and mini computers to networked PCs. In the steel industry, however, one could argue that other exogenous factors such as foreign imports have led to the decline in the U.S. steel industry. However, foreign imports peaked in the early 1980s, and declined sharply thereafter due to the continued depreciation of the U.S. dollar. Thus, foreign imports can be ruled out in explaining a continued decline in incumbent industry performance in the U.S. steel industry since the 1980s.

However, we were unable to control for the possibility that the old technology continues to perform well or even improves in performance alongside the emergent technology. This scenario seems to be particularly salient in the pharmaceutical industry: The pharmaceutical companies have been able to improve their performance based on traditional chemical-based drugs while simultaneously introducing new biotechnology drugs (Rothaermel 2001a). The observed improvement in the incumbent industry performance of pharmaceutical companies participating in biotechnology may be partly due to performance gains obtained through the introduction of traditional chemical-based drugs. Alternatively, it may be due to the employment of biotechnology as a research tool for improving the efficiency of the drug discovery process, including the process for small molecule drugs produced by traditional chemical synthesis (rational drug design). Our analysis is not fine grained enough to tease out these different effects in the pharmaceutical industry. However, we are able to demonstrate that the incumbent firms as a group have done significantly better since the mid-1980s, shortly after the introduction of the first successful biotechnology drugs. At the end of our study period, seven of the top-10-selling biotechnology drugs were marketed by incumbent pharmaceutical companies even though they had developed none of the drugs. Sales of these seven products amounted to more than \$5 billion in both 1998 and 1999 (Giovannetti and Morrison 2000), and the incumbent pharmaceutical companies appropriated about 50% of these revenues (Rothaermel 2001a).

The results for the telecommunications industry may be confounded by the regulatory decision to break up AT&T in 1984. Though one would generally expect deregulation to lead to a decline in performance as the industry moves more toward perfect competition, this has not been the case. Although the industry has shown signs of increased competition, particularly where traditional services are concerned (note the drastic decrease in the price of long distance calling), incumbent industry performance appears to have improved. Established firms have been able to take part in, and benefit from, the significant revenue stream generated by cellular telephony (e.g., estimated revenues for 1995 were \$17.4 billion) due to extensive interfirm cooperation with new entrants. This in turn contributed to an overall improvement in incumbent industry performance.

At the firm level, we found support for the importance of financial strength and R&D capability in determining postdiscontinuity interfirm performance differentials. Although it is a first step toward understanding firm heterogeneity, the focus on these two constructs can be somewhat limiting, particularly in light of some recent theoretical developments. For example, Zahra and George (2002) argued that a focus on R&D capability alone is somewhat restricting when attempting to capture a firm's capability to value, assimilate, and apply new knowledge. They reconceptualized Cohen and Levinthal's (1990, p. 138) notion of absorptive capacity as a byproduct of R&D, and suggested that researchers ought to differentiate between potential and realized absorptive capacity because potential absorptive capacity must be transformed into realized absorptive capacity in order to enhance firm performance. We follow prior empirical research in focusing more narrowly on R&D capability (Cohen and Levinthal 1989, 1990; Helfat 1994a, b, 1997) yet acknowledge Zahra and George's (2002) insight and encourage future research to go beyond R&D expenditures and attempt to find different measures that capture the multidimensionality of the absorptive capacity construct.

We also realize that there are likely other firm-specific factors that are pertinent in determining firm performance following a technological discontinuity. While we control for firm size, firm capital structure, and unobserved firm-level heterogeneity, the individual and collective significance of the firm-fixed effects open the door for future research to further untangle the firm-level capabilities necessary for superior performance following a technological discontinuity. These findings reinforce the importance of going beyond analyzing incumbents as a group and highlight the significance of heterogeneously distributed firm competencies.

Organizational Implications

An important finding of this study is that firm-level competencies are important because firms differ in their ability to adapt to a competence-destroying technological discontinuity. Thus, managers need to be cognizant about the technological and nontechnological competencies inherent in their firms. Echoing Teece (1986), managers need to recognize the different types of complementary assets and their differential importance in commercializing a new technology. Moreover, a firm's financial strength and R&D capability are not entirely independent of one another, so it is possible for managers to make adjustments in their ratio. If a discontinuity is commercialized via generic assets, managers should ensure that they have sufficient financial strength to acquire new entrants, and thereupon the new technology. If a discontinuity is commercialized via specialized assets, however, managers can redirect free cash flow to finance additional R&D activities.

Whereas R&D capabilities are built over time, the time horizon for transforming a scientific invention into a commercialized innovation (gestation period) generally takes multiple years (Hill and Rothaermel 2003); it tends to be longer the more complex the technology's underlying science. Thus, free cash flow to strengthen R&D capability should be applied as soon as the impact of the new technology on the complementary assets can be understood. This allows managers to take full advantage of the gestation period for the new technology. Depending on the magnitude of the discontinuity, it can then take a few more years after the successful development of a new technology before its performance impact becomes apparent. Thus, incumbents may be able to a obtain a first-mover advantage when adapting to a new technology if they are able to understand the impact the new technology is likely to have on their technological and nontechnological competencies prior to its manifested impact on performance. In sum, managers can substitute free cash flow for R&D expenditures and vice versa, depending on the type of complementary assets necessary to commercialize the new technology.

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Endnotes

[1]The alliance data are drawn from the MERIT CATI database (Maastricht University Economic Research Institute—Cooperative Agreements and Technology Indicators database). This is likely to be one of the most comprehensive databases covering strategic alliances worldwide over the last several decades (for a more detailed description of MERIT CATI see Hagedoorn 2002).

[2]Because a time series of quarterly ROA was not available in the telecommunications industry, we resorted to annual ROA data.

[3]There was no need to explicitly control for firm size because our dependent variables are ratios and thus are already adjusted for firm size.

[4]The possibility that any of the investigated incumbent industry performance time series could exhibit more than one break date was ruled out in all eight cases because the t-statistic for the indicator variable *break date* increased with time before peaking and subsequently declining. Thus, all eight time series exhibited exactly one statistically significant structural break.

[5]The marginally significant result for a structural break in the ROA time series and the three year difference in the break dates between the ROE and ROA time series are partly explainable by the fact that we had to resort to annual instead of quarterly data for the ROA time series, and thus significantly fewer observations constituted the time series.

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