Industrial and Corporate Change, Volume 15, Number 2, pp. 285–318
doi:10.1093/icc/dtj016
Advance Access published February 3, 2006

Technological pre-adaptation, speciation, and emergence of new technologies: how Corning invented and developed fiber optics

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This article investigates how established firms innovate and even initiate new technological trajectories. We build on and expand the notion of technological speciation to describe how a new technology emerges when a firm leverages its technological knowledge into a new application domain. Current research on technological speciation does not investigate how firms accumulate the technological knowledge which they eventually redeploy into different domains. Nor does it clarify the precise role of luck (historical accidents) and foresight (strategy) in shaping the overall process. This requires a finer grained investigation of the microprocesses and evolutionary forces underlying the dynamics of technological speciation. To this end, we use a longitudinal case study of Corning's invention and development of fiber optics technology. We focus less on testing theory and more on describing a phenomenon to generate new theoretical insight.

1. Introduction

Models of technological evolution generally describe the technology life cycle as one of incremental innovation punctuated by periods of radical innovations that spur the emergence of new technologies (e.g., Abernathy and Utterback, 1978; Tushman and Romanelli, 1985; Tushman and Anderson, 1986; Anderson and Tushman, 1990; Mokyr, 1990). During rapid change, new entrants typically outperform incumbents. Established firms under-invest in radical innovation (Henderson, 1993), fall into competency traps (Levitt and March, 1988), are hampered by their core rigidities (Leonard-Barton, 1992) or remain committed only to their main customers (Christensen, 1997). As a result, they often do not survive the new cycle of creative destruction (Schumpeter, 1934).

Contrary to common perception, however, established firms are also responsible for a large number of innovations, some of which are significant. Several studies (e.g., Methe *et al*., 1997; Rosenbloom, 2000; Ahuja and Lampert, 2001) have shown how incumbents adapt, survive, and even regain historic performance levels in markets shaken by the arrival of radical technological innovations (Hill and Rothaermel, 2003: 257). Yet, this stream of research typically focuses on the case where incumbents innovate or react to technological innovations brought about by other firms—whether diversifying entrants or newly founded firms—within an existing domain (i.e., market or industry). Less attention has been given to the case in which established firms develop new technologies, or trigger novel technological trajectories, in a different domain than those in which they currently are competing (Methe *et al.*, 1997). We believe any such study to be particularly important to shed further light on the origins of radical innovations.

Using principles of evolutionary biology, we build on the notion of *technological speciation* to examine how a new technology emerges when a firm leverages its technological knowledge base into a new selection environment (Levinthal, 1998). As it becomes adapted to the market needs and performance standards of a new domain, an existing technology can evolve into a substantially different one. The selection forces to which firms subject themselves often steer their R&D into unanticipated directions (e.g., Winter, 1990).

Focusing on the interaction with the environment is important in understanding how new technologies develop and come to commercial fruition (Clark, 1985). Current research on technological speciation is primarily concerned with the phase when an existing technology adapts to the selection criteria of a new domain; as a result, the influence that a firm's history and its technological knowledge base have on the overall process is overlooked. Evolution of the convergence between a firm's technological knowledge base and a new user environment has been similarly neglected.

Current research on technological speciation thus provides an incomplete synopsis of the microprocesses and evolutionary forces underlying the emergence of a new technology. We believe that a finer grained investigation of these processes and forces is important for at least two reasons. First, it will help identify more precisely the determinants of radical innovation at the firm level. Second, it will enhance our understanding of the role that luck (historical accidents) and strategic foresight play in technology evolution. This is clearly a critical question in strategy and innovation research; but with a few exceptions (e.g., Barney, 1986, 1997; Garud *et al.*, 1997; Cockburn *et al.*, 2000; Holbrook *et al.*, 2000; Denrell, 2004), it has not been systematically investigated.

In this article, we fill this research gap by exploring whether the knowledge firms use to develop a new technology is created in anticipation of this technology or results from knowledge accumulated in the past for other applications. Based on our analysis, we have developed the notion of *technological pre-adaptation* to describe that part of a firm's technological knowledge base that is accumulated without anticipation of subsequent uses (foresight), but might later prove to be functionally "pre-adapted" (i.e., valuable) for alternative, as yet unknown, applications (Cattani, 2004, 2005). Only by looking at the transition from this beginning phase to the phase in which a firm applies its knowledge in a new application, can we better understand the dynamics of technological speciation, especially with regard to the intersection of a firm's technological knowledge base and a new user environment.

We investigate this dynamic by focusing on Corning's pioneering research in fiber optics. Despite its radical impact in the telecommunications industry, fiber optics technology grew mainly out of Corning's long-standing expertise in specialty glass.

To date, only a few studies (e.g., Burgelman, 1988, 1994) have offered detailed accounts of how the interplay between firm-level mechanisms and environmental factors leads to the creation of new technologies and their use in commercial applications. Our analysis highlights how three evolutionary forces—technological pre-adaptation, foresight (strategy), and market feedback—shape technological evolution. Since we focus on the processes and forces that produce an observed pattern (i.e., the emergence of a new technology), a longitudinal case study design is well suited to identify these forces and examine how they interact over time. We thus advance theory on technological speciation by looking at the role of pre-adaptation in new technological developments.

The article is organized as follows. In the next section (§2), we introduce the notion of ecological speciation, elaborate on its significance for technological evolution and discuss our theoretical framework. In the methods (§3), we describe the research design, the setting, and the data. We next focus on how Corning developed fiber optics (§4). After summarizing our findings (§5), we discuss the implications and the limitations of this study and identify important topics for future research (§6).

2. Theory

2.1 Technological speciation

Firms can develop new technologies by creating absorptive capacity (Cohen and Levinthal, 1990) in a specific domain where their R&D is defined, such as Moore's law in the semiconductor industry, or by exploring a new domain through focus on different customers' needs and performance requirements. While previous research has investigated the first case extensively, the second has received less attention. Drawing from Levinthal's (1998) original notion of *technological speciation*, this study focuses on the emergence of a new technology as a result of re-deploying existing knowledge into a new selection environment.

In evolutionary biology, speciation theory describes how new biotic species come into existence. In general terms, two main processes might be at work: a new species emerges from the accumulation of evolutionary novelties within a single lineage that undergoes a gradual modification in its basic characteristics, a process called *anagenesis*, or a parent lineage splits into two or more daughter lineages, a process called *cladogenesis* (Sober, 2000: 12–13). Speciation in a single lineage cannot account for the variety of species observed in nature, because the new species eventually replaces the old one. In contrast, speciation by divergent (including disruptive) selection produces the splitting of an existing lineage into two or more species, without necessarily driving the ancestral species extinct. The primary difference between these two processes lies in the observed number of species.

The dynamics of speciation by divergent selection provides valuable insight into both the process by which technological innovation occurs and how new technologies are developed from the same technological knowledge base. In this article, we study how a firm's R&D can generate technological speciation and ultimately initiate a new technological lineage or technological trajectory (Dosi, 1982; Nelson and Winter, 1982).

Our use of the term "technological speciation" is consistent with the notion of *ecological speciation* in evolutionary biology (Schluter, 1996, 2001). Speciation theories typically explain the emergence of a new species by the initiating factors of reproductive isolation (Mayr, 1942). According to the ecological hypothesis of speciation, barriers to gene flow between populations evolve as a result of ecologically based divergent selection, that is, contrasting selection forces characterizing distinct resource environments. Under ecological speciation, reproduction isolation "evolves ultimately as a consequence of divergent (including disruptive) selection on traits between environments" (Schluter 2001: 372). This implies that populations that face different environments or exploit different resources experience contrasting natural selection pressures on traits that directly or indirectly bring about the evolution of reproductive isolation (Schluter, 2001: 373). Ecological speciation is therefore distinguished from other speciation models in which chance events play a central role, such as speciation by genetic drift or founder-events. Divergent natural selection is sufficient to trigger reproductive isolation and the eventual splitting of an existing lineage into new ones, even in the absence of a sudden genetic change (e.g., macro mutation) or geographical isolation (Schluter, 1996, 2001; Rundle and Nosil, 2005).

The analogue of ecological speciation in the development of a new technology is the application of existing technological knowledge in a new domain. Technological speciation results from "transplanting the existing technological know-how to a new application domain where it evolves in new directions" (Adner and Levinthal, 2002: 51). From this perspective, the selection forces to which pre-existing variation (i.e., technological knowledge) is subjected can ultimately generate a new technology (e.g., Clark, 1985; von Hippel, 1988).[1]

[1]For instance, wireless communications technology started as a laboratory device used by German physicist Heinrich Rudolph Hertz to measure electromagnetic waves. Hertz's laboratory device then was used by Marconi to develop wireless telegraphy. The research conducted to develop superior receivers for wireless telegraphy ultimately led to the development of the vacuum tube, which subsequently was used in radiotelephony and broadcasting (for a more detailed discussion see Levinthal, 1998; Adner and Levinthal, 2002). Wireless communications technology, therefore, underwent several evolutionary changes as a result of adapting to the specific needs of distinct domains of application.

It is important to differentiate between "a technology's *technical development* and a technology's *market application*" (Adner and Levinthal, 2002: 52) to properly understand how technological speciation occurs. While some technologies, especially science-based technologies like biotechnology are developed in research laboratories, many others develop in the course of applying existing technologies to new commercial applications. The pattern of speciation, therefore, is "far more common than is generally realized" (Adner and Levinthal, 2002: 52). As in nature, for technological speciation to occur, selection forces in a new domain must be significantly different from those faced in the other domains. The process of adapting to new market needs and performance standards ultimately leads to the emergence of a new technology.

Extant research on technological speciation (Levinthal, 1998; Adner and Levinthal, 2002) is slanted toward a description of how an existing technological knowledge becomes embodied into a new technology in the process of adapting to the needs of the new domain that it is trying to exploit—a view consistent with demand-driven explanations of technology evolution (Schmookler, 1966; von Hippel, 1988; Adner and Levinthal, 2002). This view explains how novelty (a new technology) is generated by selection acting upon existing variation (a firm technological knowledge base) but does not explain how that variation was created in the first place (e.g., Miner, 1994; Winter, 2000; Zollo and Winter, 2002). Nor does it explicitly address how the convergence between a firm's technological knowledge base and a new user environment comes about. Addressing these questions requires a fine-grained investigation of the underlying microprocesses and evolutionary forces at work. A theory on technological speciation should in fact be extended to clarify the role of luck (historical accidents) and foresight (strategy) in the evolution of technology. A critical step in this direction is to investigate the influence of a firm's history; in particular, the nature of its technological knowledge base on the actual dynamics of technological speciation. Drawing from March's (1994) idea of evolution as a process rather than an outcome, we focus on "a firm's history" to delve more deeply into the process of technological speciation.

Prior research has shown how the similarity between a firm's technological knowledge base and that required in a new domain positively affects both the decision to enter this new domain and the ability to innovate in it (Helfat and Lieberman, 2002). Despite the similarity argument, it is not entirely clear which part of that knowledge will retain its value and then be selected for new uses (e.g., Mokyr, 2000) nor is it clear if firms anticipate these applications as they accumulate knowledge in a given technological domain.

Based on our field work, we define as *technological pre-adaptation* that part of a firm's technological knowledge base that is accumulated without anticipation (foresight) of its subsequent uses, though might later on prove valuable for alternative, yet unknown, applications. In evolutionary biology, "pre-adaptation" refers to cases when "by chance, an organ that works well in one function turns out to work well in another function after relatively little adjustment" (Ridley, 1999: 347).[2] Pre-adaptation in biology assigns no role to foresight or teleology. A pre-adapted feature does not evolve in anticipation of its new function but can perform that function and is then selected to do so (e.g., the first bird feathers were for heat insulation rather than an adaptation for flight).

Firms likewise can be endowed by their past history with knowledge for reasons that are unrelated to its application in a new opportunity. Previous technologies, whether or not presently in use, often find novel applications if new environmental conditions come along. The history of technology is replete with examples of technological pre-adaptation (Basalla, 1988). For example, 3M's Post-it Notepad was based on a type of adhesive that for years "had no perceptible application—it was a solution looking for a problem" (Nayak and Ketteringham, 1994: 41).

The precise role of luck and foresight in the evolution of technology is difficult to estimate. However, the notion of pre-adaptation suggests that in the course of technological evolution, one can identify the existence of an ideal "dividing line" between the phase in which firms accumulate knowledge without anticipating its subsequent applications and the phase in which firms leverage that knowledge in a new domain as new environmental conditions and information about possible uses come along. It is at this critical juncture—when a firm's technological knowledge base and a new user environment intersect and higher levels of foresight allegedly guide the search for new technologies—that the role of strategy is particularly important.

3. Methods

3.1 Research setting

Studying the microprocesses and evolutionary forces underlying the dynamics of technological speciation required a research setting in which we could analyze not only how existing technological knowledge was leveraged into a new domain and eventually embodied in a new technology but also how that knowledge originally was accumulated. We chose Corning's invention of fiber optics for several reasons. First, Corning, founded in 1851, is one of the oldest firms in the United States, which made

[2]There is some disagreement on how expansive the concept of pre-adaptation should be. Bock (1959) does not distinguish between features that have changed and those that have retained their original function. In contrast, for Gould and Vrba (1982), pre-adaptation refers solely to features that promote fitness and were built by selection to perform the same function for which they originally evolved, while features that evolved for other usages or for no function at all and were co-opted for their current role at a later point in time are "exaptations." The usefulness of establishing whether existing features were from the outset "optimally designed by natural selection for their functions" (Gould and Lewontin, 1979: 585) is questionable. As Reeve and Sherman (1993) point out, the original roles of many observable features are virtually impossible to identify, because the phylogenetic and ecological information needed to infer such roles is unavailable or incomplete.

availability of secondary data not to be an issue. Second, we wanted to focus on one technology that was developed through the R&D of an established firm to explore to what extent Corning leveraged its knowledge base in developing fiber optics. Third, given Corning's reputation for being a highly innovative and R&D-oriented company, we expected well-established routines and practices to shape the generation of new technologies. Forth, to complement our archival data with interview data, we looked for a technology that was not too old to prevent us from interviewing people directly involved in its development. Finally, due to the recent dramatic growth in the use of optical glass fibers, especially since the advent of the Internet, Corning received extensive press coverage. This has generated a large amount of secondary data to complement interview data.

3.2 Data collection

In the analysis, we used a longitudinal case study design (Eisenhardt, 1989; Pettigrew, 1990). We adopted a historical perspective to sharpen our understanding of the phenomenon of interest as it unfolded over time (Lawrence, 1984; Kieser, 1994). Our primary objective was to identify the micro-organizational processes and evolutionary forces (internal and external to the firm) responsible for the emergence of fiber optics technology. The data collection spanned over more than three years, from early March 2002 to late September 2005. We carried out the research in three stages. During the first stage, we relied on secondary sources and company documents to develop a chronology of Corning's invention and development of fiber optics technology, from the first laboratory experiments to its commercial application. Next, we conducted three rounds of interviews with managers from Corning at different points in time to discuss our initial timeline and collect additional data. Finally, we conducted another round of interviews and analyzed internal documents and memos dating back to the period when Corning identified the new investment opportunity and decided to go after it.

The overall research process was highly iterative (e.g., Miles and Huberman, 1984). Framing the emergence of a new technology as a speciation event partly influenced the type of data we collected, leading to an emphasis on gathering data at the level of Corning's technological knowledge base, the market needs and performance standards it faced within the fiber optics market and its business strategy. Yet, the data collection was not purely influenced by a theory defined a priori. In the process of interpreting the data and studying the microprocesses and evolutionary forces underlying the phenomenon of interest, not only did we wrestle with the challenge of establishing a clearer link between those processes and forces and the various stages of technological speciation, but during that process we also defined more precisely our theoretical constructs.

3.2.1 Stage 1: analysis of archival data

During the first stage, we consulted multiple data sources that dealt with the development of fiber optics and optical communications, both internal (annual reports, organization charts, and technical papers available on the company web site) and external (specialized books, newspaper articles, academic papers, case studies, and industry reports) to Corning. Two books, *Winning in High-tech Markets* by Morone (1993) and *The Silent War* by Magaziner and Patinkin (1989), describe the environmental and firm-specific conditions that favored the emergence of fiber optics at Corning. We also found historical and technical details on fiber optics technology and Corning in particular in Hecht's book *City of Light* (1999). Based on these sources, we defined a preliminary road map of crucial events and factors that shaped the evolution of fiber optics and the role Corning played in this process.

Since patent data provide a detailed, consistent chronology of when certain technical knowledge was first created, we used them to estimate when Corning began to explicitly develop fiber optics for long-distance applications. We analyzed the three key patents, No. 3711262, 3659915, and 3737293 (Table 1), that fostered the emergence of fiber optics and its subsequent use as a light-transmitting medium in an optical communications system. While examining the content of each patent as well as backward citations and claims, we looked for any explicit reference to the use of optical glass fibers for communications to establish when this application first became evident. We validated our analysis of the patents by discussing some of the technical issues with an academic expert in the field of optical communications.

3.2.2 Stage 2: interview data

We conducted two rounds of semi-structured interviews with R&D managers at Corning's photonics plant. While on our first visit in March 2002, we interviewed five managers from different functional backgrounds with the help of a research assistant. All but one had direct experience in fiber optics. Among the interviewees was Donald Keck, one of the three inventors of the first low-loss optical glass fiber in 1970 (at the

Table 1 Corning's early key patents in fiber optics

Invention	Patent number	Inventor	Class/sub-class	Filing year	Issue year
Method of producing optical waveguide fibers	3711262	D. B. Keck and P. C. Schultz	65/417	1970	1973
Fused silica optical waveguide	3659915	R. D. Maurer and P. C. Schultz	385/142	1970	1972
Method of forming an economic optical waveguide fiber	3737293	R. D. Maurer	65/417	1972	1973
Method of producing glass by flame hydrolysis	3859073	P. C. Schultz	65/60.51	1973	1975
Germania containing optical waveguide	3884550	P. C. Schultz	385/142	1973	1975

time of the interview, he was directing optics and photonics research activities). The interviews lasted from one to three hours each and were open-ended.

During the interviews, we asked managers to discuss the context in which fiber optics emerged, the technical issues encountered in developing this technology, and how it evolved within Corning with regard to market demand and competition. A second set of questions dealt more specifically with "why" and "how" Corning decided to invest in fiber optics. Our goal was to better understand how Corning identified this new investment opportunity: was it intentionally searching for it? Given Corning's track record as a glass manufacturer, we asked managers whether fiber optics was essentially an outgrowth of Corning's long-standing base of experience in specialty glass or if it had to create/acquire entirely new resources and capabilities. Finally, we raised questions about how Corning tried to create its competitive position within the new market. The managers directed our attention to some important technological antecedents as well as organizational factors we initially had overlooked. They also recommended two books, *Corning and the Craft of Innovation*, by Graham and Shuldiner, and *The Generations of Corning*, by Dyer and Gross, which were both published in 2001 to celebrate Corning's 150-year anniversary. These books include several excerpts from internal documents and memos, so they helped us to better understand how Corning decided to invest in fiber optics and the first steps it took to implement this decision. Since we were only allowed to take notes, we compared our notes with those of our research assistant the day after the visit, discussed differences, and listed issues requiring further clarification.

During the second one-day visit in June 2002, we attempted to fill in the gaps in our data and clarify a few issues. The manager who accompanied us during this visit helped us verify our road map of events, define a more precise timeline and discuss various technical problems associated to the development of fiber optics. The visit gave us the opportunity to double-check our list of relevant patents, look at early annual reports to find any explicit reference to fiber optics, and collect additional industry data.

In the spring of year 2004, we further honed our analysis and interpretation of relevant events by conducting a three-hour telephone interview followed by a series of email exchanges over several months with Tom MacAvoy, Corning's former president. He experienced the phases "before" and "after" the emergence of fiber optics and played a critical role in its development. We further questioned him about the timeline in fiber optics development. Since he went through all the phases and was also one of the key decision-makers, we asked him explicitly how Corning recognized that its stock of knowledge could be leveraged in fiber optics and actually used to create a new business.

3.2.3 Stage 3: additional interviews and analysis of internal documents

During our third and last visit to Corning in May 2005, we met with several key figures: Donald B. Keck, at the time retired vice president and executive director of research; Alfred L. Michelson, former head of Corning's patent department; Stuart Sammis, currently Corning chief archivist; and Tom MacAvoy, former president of Corning, who played a critical role in arranging the visit and involving the other interviewees. The meeting lasted about 8 hours and proved a unique opportunity to clarify important issues and collect additional data. While Keck and MacAvoy experienced most of the events before, during, and after the invention of fiber optics, Michelson joined Corning a few years later and Sammis even more recently. This somehow heterogeneous composition of interviewees had two major advantages. First, different recollections of important decisions, initiatives and events, and different perspectives on specific issues could be contrasted and compared. Second, during the discussion, strong agreement on many important questions was achieved.

Our last visit to Corning also gave us the chance of having access to internal memos/documents dating back to the period when Corning first learned about the new investment opportunity, explored its feasibility, and decided to start the first laboratory experiments. Thanks to these data, which complemented our archival and interview data, we had the opportunity of examining some of the early critical decisions and initiatives in the development of fiber optics through the eyes of the people involved, at the very moment those decisions and initiatives were taken. Overall, we collected 11 such documents, with the first dating 17 June, 1966 and the last 23 May, 1967. Partly for privacy reasons and partly for convenience, we numbered them to reflect their temporal sequence—with document No. 1 preceding document No. 2 and so on.

This study is retrospective and therefore has the advantage of knowing the "big picture"—that is, "How things developed and the outcomes that ensued" (Van de Ven and Poole, 2002: 875). Yet, we believe the triangulation that resulted from our multiple, distinct data collection reduces not only construct validity problems but also the bias that potentially afflicts any historical studies. Besides allowing us to identify more precisely some crucial technological antecedents and organizational factors that favored the emergence of fiber optics, this triangulation lowers the risk of retrospectively imposing meaning on historical events based on our knowledge of outcomes (Aldrich, 2000). Moreover, because the people we interviewed were present at different points in time in Corning's history, we could reconstruct more accurately how fiber optics emerged (Tripsas and Gavetti, 2000). This combination of sources helped us overcome the limitations of each separate source. Indeed, "the most important advantage presented by using multiple sources of evidence is the development of *converging lines of inquiry* . . ." (Yin, 1994: 92).

4. Development of fiber optics at Corning

We divided the study into four phases in order to present the evidence coherently while keeping its underlying continuity in mind. Each phase characterizes the dynamics of technological speciation as it unfolds over time. Besides studying technological speciation in the context of changes at other levels of analysis (e.g., environment), we also recognize the importance of "temporal interconnectedness, locating change in the past, present, and future time" (Pettigrew, 1990: 269).

The first period (pre-1966) coincides with the phase in which Corning accumulated knowledge in different but related fields. It is during these years that Corning created its "pre-adaptation" with respect to fiber optics. During the second period (1966–1970), Corning conducted the first laboratory experiments after identifying the new investment opportunity, largely relying on its prior experience in specialty glass in an effort to satisfy the needs and performance standards (i.e., selection criteria) of the nascent fiber optics market. A clearer strategy for this new business gradually emerged. During the third period (1970–early 1980s), Corning conducted the first trials and small-scale applications of the new optical fibers with more explicit market feedback guiding its R&D. It explored the commercial feasibility of the new technology and defined more clearly its competitive strategy. During the last period (post-1980s), a sizeable market for fiber optics emerged and more resources became available to the firms that entered into it.

4.1 Pre-1966 period: from specialty glass to fiber optics technology

Corning Inc. began operating in 1851. By 1876, it produced several types of technical and pharmaceutical glass. It also developed the red-yellow-green traffic light system and borosilicate glass that can withstand sudden temperature changes and is used to produce *Pyrex* bake ware and laboratory ware. Corning's invention and commercialization of *Pyrex* marked the beginning of its cookware and scientific laboratory-ware businesses.

In the 1930s, Corning scientist Frank Hyde invented the *flame hydrolysis* process to manufacture *fused silica* using the vapor deposition method. The relevant patent—*Method of Making a Transparent Article of Silica* (No. 2272342)—was filed on 27 August, 1934 and granted on 10 February, 1942. Another Corning scientist, Martin Nordberg, further perfected the process a few years later by finding that the introduction of an oxide additive (more precisely, titanium oxide) into glass (e.g., fused silica) produced by flame hydrolysis reduced its thermal expansion almost to zero near room temperature (Hecht, 1999). This invention led to the patent *Glass Having an Expansion Lower Than That of Silica* (No. 2326059) that was filed on 22 April, 1939 and granted on 3 August, 1943. The vapor deposition method was originally used at Corning in applications such as telescope mirrors, spy satellites, and ceramics during the 1960s. The first commercial application came in World War II, "when Corning used it to make electronic delay lines for radar systems under a highly secret contract with the Signal Corps" (Graham and Shuldiner, 2001: 132). These inventions proved to be important precursors in the late 1960s and early 1970s when Corning pioneered the first low-loss optical glass fiber using the vapor deposition method (see 1966–1970: From laboratory experiments to the first low-loss optical glass fiber).

By the 1950s, Corning had built a plant to manufacture fused silica—though mainly for defense applications—and was the only firm in the world with a furnace that could heat glass at very high temperatures (around 3600°F) to melt fused silica and draw it into fibers. During this period, Corning also leveraged the capabilities in the production of radar bulbs—developed during World War II—to produce television bulbs. Furthermore, it concentrated on the development of new glass–ceramics materials. These efforts led to the invention of Pyroceram—which gave birth to a new family of cookware known as "Corning Ware." In the 1960s, Corning was active in several glass– and glass–ceramic-based businesses. The television bulb business was taking the lion's share, accounting for about half of the revenues and three-quarters of the profits (Table 2).

Around this period, the growth prospects in some of Corning's traditional businesses began to decline. Japanese television manufacturers were gradually displacing Corning's US-based customers—mostly color television set manufacturers—in the largest business, the television light-bulb market. By 1969, imported black and white televisions represented 43% of the US market, up from just 16% in 1965. Also, other newly created businesses did not produce the expected results. One such business was the production of safety windshields for the automobile industry. Although the safety windshield project was terminated, Corning developed a new process to draw thin, high-quality specialty glass that "formed the basis for what appeared to be an enormous new business opportunity by 1990 – flat glass for liquid crystal displays" (Morone, 1993: 133). Equally unsuccessful was the development of the "heat exchanger"—called *Cercor*—a key component for automotive gas turbine engines. Yet, the use of gas turbines for automobiles was still a remote commercial possibility in those years. Although the gas turbine engine heat exchanger was not successful, in the early 1970s Corning leveraged this technology to develop *Celcor,* the ceramic substrate catalytic converters for

Table 2 Corning's businesses in 1970

Business segments	% of total sales
Consumer (cookware)	25
Television bulbs, light bulbs, resistors and capacitors, Signetics (computer terminals)	50
Medicine: pharmaceutical glassware, ophthalmic glass	25
Science: laboratory glassware, chemical analysis instruments	
Construction: Pyroceram	
Industrial systems and equipment: glass equipment for high-temperature process industries	
Transportation: safety windshield, headlight components	

emissions control, in which it became one of the market leaders. In 1962, Corning acquired Signetics, a spin-off from Fairchild semiconductor, to enter into electronics—more precisely, the promising integrated circuits business. In the period right after WWII, Corning developed tin oxide-based resistors, as well as glass capacitors—passive electronic components widely used in the 1950s and 1960s. By establishing a position in active circuit components Corning thus gained a much broader view of the electronic industry. While Signetics was sold off in 1975, Corning capitalized on its expertise in electronics to develop optical fibers.[3]

Corning first became involved in fiber optics technology in June 1966, when Corning's senior researcher William Shaver was invited to attend a meeting with a delegation from the British Post Office (BPO) and representatives of the British government at Electrosil, Corning's subsidiary in Sunderland, England. The BPO, which then operated the British telephone network, invited several glass companies, including Corning, to discuss the possibility of renewing the telecommunications infrastructure of the country by replacing copper-based fibers with optical glass fibers. At the time, William Shaver was serving as International technical liaison for R&D. During the visit to Electrosil, Shaver was informed of the BPO's interest in the development of glass fibers that could be used for light transmission in telecommunications. The BPO, like other long-distance telecom companies, was dissatisfied with existing copper fibers that lacked the carrying capacity required to handle increasingly larger amounts of data and information. Researchers from the Standard Telecommunications Laboratories (STL), International Telephone and Telegraph's (ITT) subsidiary in England, argued that optical glass fibers could theoretically provide the desired capacity if light attenuation (i.e., loss of signal strength due to impurities in the materials) could be reduced.

In March 1966, at the Institution of Electrical Engineering (IEE) in London, Charles K. Kao and George Hockham, both engineers at STL, presented a paper published in the Proceedings of IEE in July of the same year. In the paper, they identified some of the key problems that should be overcome to develop a practical optical fiber like light absorption losses caused by the presence of impurities such as iron in the glass and light scattering losses caused by core/cladding interface imperfections.

To carry light, in fact, the refractive index of the clad (the outer part of the fiber) has to be less than the refractive index of the core. Kao and Hockham suggested that light absorption by impurities could be reduced by using an extremely pure glass, for example, fused silica. They also speculated that optical fibers would be a suitable transmission medium for long-distance communications if attenuation could be kept under 20 db/km, that is, at least 1% of the light entering a waveguide would remain after traveling 1 km. Satisfying the 20 db/km threshold was necessary to make the use of light in long-distance communications economically viable and

[3]We thank Tom MacAvoy, Corning former president, for bringing this point to our attention.

avoid using amplifiers to revitalize the intensity of the light signal after it had traveled only a short distance.[4]

Although the paper demonstrated for the first time the theoretical feasibility of optical communications and posed several critical questions, it offered no practical solution to them. Other scientists and researchers also were independently conducting research on fiber optic communications. For example, French engineer Alain Werts at Thompson CSF in France published in 1966 a proposal similar to that of Kao and Hockham in the journal *L'Onde Electronique*; however, Thompson CFS did nothing to explore the viability of the proposal due to lack of funds (Hecht, 1999).

As a result, prior to 1966, optical fibers were used to transmit light for illumination or as elements of an optical image—for example, in endoscopic probes. American Optical Company (AOC), for instance, tested the first fiber-optic endoscope on a patient in 18 February, 1957. During the Cold War, optical fibers were applied in airplane and ship communications systems, because they promised to withstand nuclear effects better than metal wires (Hecht, 1999). These conventional optical fibers were capable of transmitting light of practical intensity only for very short distances (a few meters) due to the poor transmission efficiency (high attenuation). The best available fibers had attenuation of 1000 db/km—only 1/1000 of the original light signal remained after traveling 1 km—making them unsuitable for light transmission over long distances.

Against this backdrop, the BPO's suggestion of producing low-loss optical glass fibers for telecommunications seemed worth pursuing. After his visit to Electrosil, where the development of a fiber optics transmission system for multiple channel communications was first discussed, William Shaver wrote a memo to inform Corning's top management about the meeting (Document No. 1, 17 June 1966, p. 1):

> The problem discussed was the development of special glass fibres for transmittance of information (voice type and other) over long distances using modulated laser beams. This requires high light transmittance fibres with a loss of not more than 20 db per kilometer. They [the BPO and the Ministry of Defense] are asking if Corning would undertake the development of such a fibre and on what terms. This project is of great interest, both for commercial and defense applications. They would expect to have continuous fibre cables between 1 and 2 km long with repeater amplifiers

[4]The 1 April, 1966 issue of *Laser Focus* noted Kao's proposal: "At the IEE meeting in London last month, Dr. C. K. Kao observed that short-distance runs have shown that the experimental optical waveguide developed by Standard Telecommunications Laboratories has an information-carrying capacity . . . of one gigacycle, or equivalent to about 200 TV channels or more than 200,000 telephone channels . . . Despite the fact that the best readily available low-loss material has a loss of about 1000 db/km, STL believes that materials having losses of only tens of decibels per kilometer will eventually be developed."

> at intervals of about 1.5 km. The time program is estimated at 3 years for development of the system and large scale use in 10 years.

Yet, at that time, Corning had no explicit strategy to use optical fibers in telecommunications. Nor was it clear how to meet the 20 db/km threshold. As Charles Lucy, who later became the head of the optical fiber business development group, succinctly stated (in Magaziner and Patinkin, 1989: 276):

> We didn't really know a thing about telecommunications

Year 1966 turned out to be crucial for the development of fiber optics for several reasons. First, the publication of the paper by Kao and Hockham did the theoretical groundwork for fiber optics and eventually fostered the first wave of laboratory experiments to meet the 20 db/km threshold. In addition, the BPO's intention to renew the telecommunications infrastructure of the country using optical glass fibers signaled the existence of a potentially profitable market.[5] Finally, thanks to Shaver's visit to England, Corning spotted this new investment opportunity. At a time when light-transmission over long-distances was viewed more as a theoretical rather than a concrete possibility, a clearer sense of direction started to emerge in the late 1960s.

In this sense, 1966 represents an ideal dividing line between a time when Corning conducted its R&D without anticipating its subsequent importance for developing fiber optics and the period when higher levels of foresight presumably guided such efforts. It was during this phase that Corning (unintentionally) created the conditions that eventually favored the convergence with a new user (telecom companies) environment. Indeed, thanks to the experience accumulated with fused silica, vapor deposition, light scattering, and electronics, Corning found itself in an advantageous position in developing fiber optics.

4.2 1966–1970: From laboratory experiments to the first low-loss optical glass fiber

In the meetings that followed, including subsequent visits to the BPO, Corning decided to explore the feasibility of low-loss optical glass fibers. The challenge was to satisfy the market needs of long-distance telecom companies interested in using a more effective transmission medium than traditional copper fibers to handle

[5]After a visit to England, for instance, Maurer reported that "The load on the British communications system is growing at about 18 per cent per annum and the growth is expected to increase. The present system, including aerial microwave relay, will be obsolete in about five years. The main reasons for this are the same as in the United States: viz video transmission, including broadcast, closed circuit systems, and video telephone; and computer interconnections. The video telephone is expected to be in use in London in a couple of years. Increasing the number of telephone lines is a hopeless situation and higher capacity communication systems (i.e., faster equipment) is the only way out" (Document 7, January 19, 1967, p. 1).

increased amounts of traveling data and information. In terms of performance standards, this meant producing fibers with a very low level of attenuation (below 20 db/km) to avoid the use of amplifiers to revitalize the intensity of the light signal after a relatively short distance. Thus, the 20 db/km threshold was critical to make a long-distance optical communication system economically viable.

The first step was to form a dedicated research team, which included Donald Keck and Peter Schultz under the guidance of Robert Maurer. They put optical fibers on a list of potential projects for graduate students during the summer of 1967 (Hecht, 1999). Before joining the team, Peter Schultz was seeking to resurrect the vapor deposition process—a technique used at the time at the Canton plant north of New York to produce mirror blanks—while researching fused silica in the glass chemistry department. Maurer was the natural candidate to develop the first low-loss optical glass fiber as he had worked with fused silica since 1956 and had researched light scattering, a major cause of fiber attenuation. He was among the Corning scientists who had been investigating glass-based lasers since the late 1950s. The laser work yielded nothing, but, as Tom MacAvoy recalled, "the result was that we had about 20 people who understood quantum optics" (Morone, 1993: 135). Chuck Lucy, who had been in charge of fiber optic faceplates business since 1963, sponsored Robert Maurer's research.

To develop the first low-loss optical fiber, the research team concentrated on Corning's core knowledge in specialty glass technology. Other firms discarded fused silica, because its refractive index was too low for fiber cores and its melting temperature too high, but Corning had worked with it for three decades. Corning was the only firm in the early 1960s with a furnace that could heat glass to 3600°F to melt fused silica and draw it into fibers. As Keck (2000: 2) later noted, "the process of vapor deposition, invented by Frank Hyde for use in *other* [emphasis from the authors] Corning technologies became part of the fiber-making process."

Concurrent advances in laser technology and other key components facilitated the emergence of long-distance optical communications. In 1970, for instance, AT&T Bell Labs discovered how to operate a semiconductor laser continuously at room temperature, which made it possible to generate large amounts of light in a spot tiny enough to be sent through optical fibers (Hecht, 1992). To test the properties of the new fibers his team was trying to develop, Maurer established a working relationship with Stewart Miller who at the time was the coordinator of research on optical communications at AT&T Bell Laboratories. Thanks to this collaboration, Maurer and his research group had the chance to promptly embrace the latest advances in light emission and detection. The development of optical communications, however, was still viewed merely as a theoretical possibility. In an article published in *Science* in 1970, Stewart Miller emphasized how existing glass fibers were unsatisfactory and anticipated their long-distance use only in a more distant future. While Miller recognized that glass fibers appeared a viable solution, alternatives transmission media, especially confocal lenses, were still receiving much attention.

Despite these prospects, the possibility of using optical glass fibers for commercial applications was first demonstrated in 1970 when Maurer, Keck, and Schultz developed the first single-mode glass fiber with attenuation below 20 db/km. Two of the three key patents, *Method of Producing Optical Waveguide Fibers* (Patent No. 3711262) and *Fused Silica Optical Waveguide* (Patent No. 3659915), were filed in 1970 (Table 1). The third key patent, *Method of Forming an Economic Optical Waveguide Fiber* (Patent No. 3737293), was filed in 1972. These patents laid the foundations for implementing fiber optics. Each patent application emphasizes possible uses in communications systems and also mentions the inventions by Hyde and Nordberg as crucial antecedents. No single prior patent cited by these three ever explicitly indicated communications as a possible application. The only exception is a patent filed in Japan in 1968 by the Semiconductor Research Foundation Kawauchi, two years after Kao and Hockham's paper was published.

This is when Corning began to leverage its base of experience as it learned about the new application for which it was potentially pre-adapted. Since the range of possible applications for a firm's technological knowledge base is typically wider than its applications at any given moment, firms can capitalize on previous technological investments by transferring over time knowledge already available in-house—a capability that Garud and Nayyar (1994) have defined as "transformative capacity."

Corning had the ability to do this for several reasons. In line with its strong R&D-based culture, Corning usually developed new technologies and businesses internally, mostly by leveraging its core technical competencies.[6] The conviction that scientific innovation is important has always been an integral dimension of the corporate culture virtually from its beginning. For instance, in 1908, Corning first established an R&D laboratory under the direction of Dr. Eugene Sullivan. In 1957, a new corporate R&D laboratory was built. R&D spending rose from 3.5% of sales during the 1950s up to 5% by the mid-1960s. This corporate belief in supporting innovation contributed to creating an environment where new ideas and initiatives were consistently generated and errors/mistakes seen as valuable learning opportunities. Especially during the 1960s and the 1970s, researchers and scientists "were given wide latitude and substantial resources, and they were encouraged to pursue their interest—regardless of the immediacy of a financial payback" (Dyer and Gross, 2001: 279).

An important element of this culture was the belief that errors or mistakes represented valuable learning opportunities, as this quote from William Armistead, vice president for R&D and vice chairman for technology during the 1970s suggests (in Morone, 1993: 135):

> . . . if you keep track of your projects over a period of years, you will find that one-third of them are technical failures where you couldn't accomplish what it is you wanted to accomplish. The other two-thirds split 50-50.

[6]A few years later, the 1985 *Annual Report* (p. 3) stressed how fiber optics was " . . . a classic example of a Corning-developed, Corning-patented technology . . . "

> Half of them are big commercial successes and the other half are big commercial failures. Although they are technically successful, for whatever reason, the customer won't buy. Now, how can you stand half failures? Well, you have to have them. If you want any success at all, you've got to have the failures too. I could never figure out which was which in advance.

A well-established practice at Corning was to send out senior researchers (like in the case of William Shaver) to visit research laboratories and existing or potential customers, attend conferences, etc. When William Armistead was head of corporate R&D, two to three senior researchers who were well known in the scientific community and with a wide knowledge of Corning's technical skills were asked to act as Corning's R&D ambassadors. The main objective of having "technology scouts," akin to that of gatekeepers (e.g., Allen, 1977; Allen, Tushman, and Lee, 1979), was to spur innovation by facilitating the acquisition and diffusion of knowledge, both technical and at the market level.[7] This practice permeated Corning's behavior to consistently seek applications for which it had potentially valuable knowledge. New technologies were developed and came to commercial fruition as a result of re-deploying existing knowledge into new domains of application (Abernathy and Clark, 1985; Clark, 1985).

Other organizational practices and routines played a critical role as well. Retaining long-tenured employees helped preserve the integrity of the firm's knowledge base and make new syntheses as novel opportunities came along. For instance, before becoming involved in the development of fiber optics, Robert Maurer gained valuable experience with light scattering and quantum optics. Low turnover rates among managers, senior researchers, and engineers ensured continuity between past and current R&D. Although previous research has argued that organizational memory does not necessarily coincide with individual memory (e.g., Nelson and Winter, 1982; Walsh and Ungson, 1991), individuals are often "the sole storage point of knowledge that is both idiosyncratic and of great importance to the organization" (Nelson and Winter, 1982: 115). While problems tend to change continuously, the same body of knowledge can remain valuable as individuals "recognize similarities between old solutions and new problems" (Hargadon and Sutton, 1997: 732).

It is worth noting that the main R&D efforts were located in the small town of Corning. Not only was the central laboratory located in Corning but the senior management continues to operate from there. This intimate atmosphere around the Corning area was an important factor in creating a sense of community and fostering the exchange of knowledge through multiple channels even outside the firm.[8] As a result,

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[7]In line with this long-standing practice was the institution in 1990 of the Outstanding Publication Award. Each year, an internal committee of scientific peers assigns the award to a paper published by a Corning scientist that the company believes stands out for its scientific excellence and best represents a significant advance in science and technology.

[8]This point was made by several of our interviewees, who stressed it as one of the main reasons why they wanted to work for Corning.

the process of storing, retaining, and retrieving knowledge was greatly enhanced beyond formal organizational channels such as meetings or brainstorming sessions (Walsh and Ungson, 1991; Hargadon and Sutton, 1997).

The combined effect of these conditions (low turnover and concentration of R&D activity in Corning town) fostered intense social interaction both inside and outside the company. This, in turn, favored the development and maintenance of what Nahapiet and Ghoshal (1998) describe as the structural (network ties), relational (trust and identification), and cognitive (shared codes and language) dimensions of social capital.

To summarize, the previous conditions (corporate culture, search routines and practices, social interaction) not only represented key dimensions of Corning's transformative capacity, they also fostered an ongoing process of variation-selection-retention (Burgelman, 1983; Miner, 1994; Zollo and Winter, 2002) by which new knowledge was consistently generated, selected, and retained in the search for adaptive advantage within existing and new domains of application.

4.3 1970–1980s: From laboratory experiments to the first commercial applications

After the path-breaking work that started in the late 1960s and led to the first patents in the early 1970s, further production refinements for optical fibers were achieved during the 1970s and 1980s. To prevent light from escaping the core of the fiber, the refractive index of the core had to be larger than that of the cladding layer. The higher the difference between the two indices, the lower the amount of light that escapes. Since fused silica had a low refractive index, dopants such as titanium were used to increase the index. These materials however did not provide the structural strength for long optical waveguides. In 1972, by enhancing the flame hydrolysis process and using germanium to increase the refractive index of the fiber core, Schultz was able to manufacture fibers with attenuation loss of 4 db/km. At these levels, optical fibers could carry the light signal for 20 km without the need for a repeater to revitalize it. Conventional copper fibers required a repeater every 6 to 8 km (patents No. 3859073 and No. 3884550 in Table 1).

The following excerpt from the 1975 *Annual Report* illustrates fiber optics' growing importance within Corning's communications business segment:

> Corning scientists recently demonstrated the use of a single fiber more than six miles long that can carry the equivalent of 33,000 telephone conversations through a core the diameter of a human hair . . . The company's program involves close technical cooperation with Bell Telephone Laboratories and other major telecommunications companies around the world. Initial field evaluations of optical cables and communications systems using Corning waveguides are scheduled by these companies in

> 1976. Pilot use indicates Corning waveguides can be competitive in cost with coaxial cable (pp. 8–9).

Fibers are but one component of an optical communications system and Corning had limited to no experience in other components. It needed to access other firms' expertise. In 1977, Corning integrated vertically to cable production by creating Siecor, a joint venture with Siemens, which continues to be its manufacturing arm for optical cables. Siecor received its first order for optical cables from General Telephone Company of Fort Wayne (Indiana) in 1978. Most of the customers at the time were independent telephone companies.

After the creation of Siecor, the next step was to convince telephone companies of the advantages of using optical glass fiber cables and to overcome the skepticism and resistance of the cable manufacturers who were intermediaries between Corning and telecommunications firms. Many cable producers signaled their commitment to more conventional technologies by expanding their copper-cable-manufacturing capacity. Corning's efforts to develop the US market were particularly hindered by AT&T's 80% monopoly of the US phone market and its decision to produce optical fibers in-house (Nanda and Bartlett, 1993). Other potential US customers were not inclined to invest in optical fibers, as they forecast their widespread use only in the distant future. Similarly, industry experts predicted scant demand until the twenty-first century.

Searching for new markets, Corning formed several partnerships in the early 1970s with cable-makers such as Siemens in Germany, Pirelli in Italy, BICC in UK, public laboratories in France and Furukawa in Japan. In general, each partner was expected to develop waveguide components and cables. In return, Corning agreed to license its patents and know-how to make waveguides in the partner's country. Since these partnerships involved companies with the capability of producing copper cables, these license agreements allowed them to develop the techniques for cabling glass fibers. Corning could thus rely on experienced partners who were committed to the new technology. Thanks to these partnerships, Corning collected annual fees to fund its R&D efforts in fiber optics. It also relied on these fees to acquire the complementary assets required to build and defend its competitive position in those markets (Teece, 1986).

In doing so, it implicitly granted its partners the right to produce fibers. As a result, in order to compete in optical fiber, Corning had to be the technological market leader. As part of a strategy of continuously improving existing processes and new product development, Corning decided to establish a business unit devoted solely to the production of optical fibers. It complemented this strategy by defending its intellectual property aggressively on the premise that its know-how was the key isolating mechanism to secure a viable market position, retain the technological lead and garner yields accruing to its R&D (Rumelt, 1984; Teece, 1986). An example of this strategy was Corning's victory in two litigations for patent infringement; the first against

ITT, which eventually agreed to pay Corning and license its technology for any subsequent use, and the second against Sumitomo Electric USA, another major competitor in fiber optics.[9]

4.4 The 1980s and beyond: the commercial success of fiber optics

In the early 1980s, the commercial success of fiber optics was still uncertain. By 1982, Corning's fiber optics business was generating about $10 million in revenues. This was up from $1 million in 1975, but these were not significant profits. The European joint ventures were also only marginally profitable. Most of the sales consisted of experimental trials—for examples, samples of optical fibers sold to phone companies interested in testing the potential of light transmission or small orders placed by independent phone companies. Until 1980, large-scale applications for optical fiber cables and related technologies remained rare in the United States, with sales of about $40 million (Fortune, 1980).

Corning's sustained commitment to fiber optics helped it extend its advantage over competitors, especially AT&T, which delayed adoption of fiber optic cables as a substitute for copper-based cables. Furthermore, Corning benefited immeasurably from two pivotal events. First, in 1982, Microwave Communications, Inc. (MCI) decided to build the first long-distance telephone network in the United States using single-mode optical fibers to counter AT&T's dominance of the long-distance network market. It purchased 100,000 km of single-mode fiber from Corning for $90 million, by far the biggest order that Corning had received. GTE Sprint and U.S. Telecom followed MCI, placing orders of similar magnitude. Demand in North America increased from 200,000 km in 1982, to 600,000 km in 1984, to 1.6 million km in 1986 (Morone, 1993: 165). In 1986, Corning sold more than $220 million of optical waveguides, or about 12% of Corning's total sales that year, with operating margins of over 23% (Dyer and Gross, 2001).

MCI's order also established single-mode optical fibers as the new standard for optical fibers. Although the first low-loss glass fiber that Corning developed was a single-mode fiber, multi-mode fibers—much easier to produce—were the standard. Corning had only limited experience in the production of single-mode fibers, but it was among the first firms to develop and produce them, which gave it the chance of moving faster along the learning curve and gaining an edge over competition. Second, the government's forced split-up of AT&T in 1984 was a boon to Corning. From this split-up, eight firms emerged: AT&T and seven regional service providers. The split-up not only aided competition in the long-distance market but also "allowed entrepreneurial

[9]We thank Alfred L. Michelson, former head of the patent Department at Corning, for sharing with us the documentation regarding the decision of the U.S. District Court Southern District of New York (5 USPQ2d 1545) on the patent infringement litigation between Corning (at the time still Corning Glass Works) and Sumitomo Electric USA Inc. The documents proved to be an invaluable source of technical, historical, and company data.

companies to challenge the existing technologies and embrace optical fiber to build new telecom networks" (Keck, 2000: 1).

Due to the growing importance of the telecommunications business and its increasingly large presence in the medical business, Corning decided to drop "Glass Works" from its name on 28 April, 1989. As Corning Glass Works Chairman James R. Houghton declared ". . . the new name acknowledges the transformation of the company beyond its historic base in glass . . .We will remain the No. 1 company in the field of specialty glass and specialty ceramics" (*Annual Report*, 1989: 5). Corning's overall portfolio of businesses was streamlined, and the focus progressively shifted toward telecommunications which, by 1985, had become "a major contributor to income from operations" (*Annual Report*, 1985: 3).

More recently, the deregulation of the telecommunications industry by the Telecommunications Act in 1996 further bolstered the use of fiber optics. More than 3000 new service providers began operating between 1997 and 2000 (Standard & Poor's, 2000). The Internet's rapid growth spawned new investment opportunities, such as server connections, and stimulated the search for additional advancements in optics-based technology. In 1970, Corning's telecommunications business was not yet born (Table 2). By the fiscal year 1999, it accounted for 60% of the \$4.741 billion in firm revenues and 71% of the \$6.272 billion in firm revenues during the 2001 fiscal year (see the 2000 and 2002 *Annual Reports*).

5. Discussion

The previous sequence of events highlights the dynamics of technological speciation as a result of an established firm redeploying part of its existing technological knowledge base into a new domain of application. More specifically, four distinct phases shaped the evolution of fiber optics (Figure 1). Prior to 1966, Corning developed what we define as *technological pre-adaptation*—that is, knowledge accumulated over time in various types of specialty glass and other technical fields (e.g., electronics) but without anticipating its subsequent use in the production of optical fibers for long-distance applications. For example, the production of glass fibers for medical and military applications, although significantly different from techniques employed in telecommunications, allowed Corning to gain valuable experience. Also, the experience in a seemingly unrelated field like electronics proved to be very important.

Although the previous argument recalls a real-option perspective on organizational resources (Bowman and Hurry, 1993; McGrath, 1997), there are also important differences. The notion of technological pre-adaptation is somewhat consistent with that of a shadow option, whereby an existing bundle of resources provide options (or investment opportunities) awaiting recognition. These options exist only when decision makers recognize them (Bowman and Hurry, 1993: 763). This occurs when new information about possible applications for a firm's knowledge stock gradually

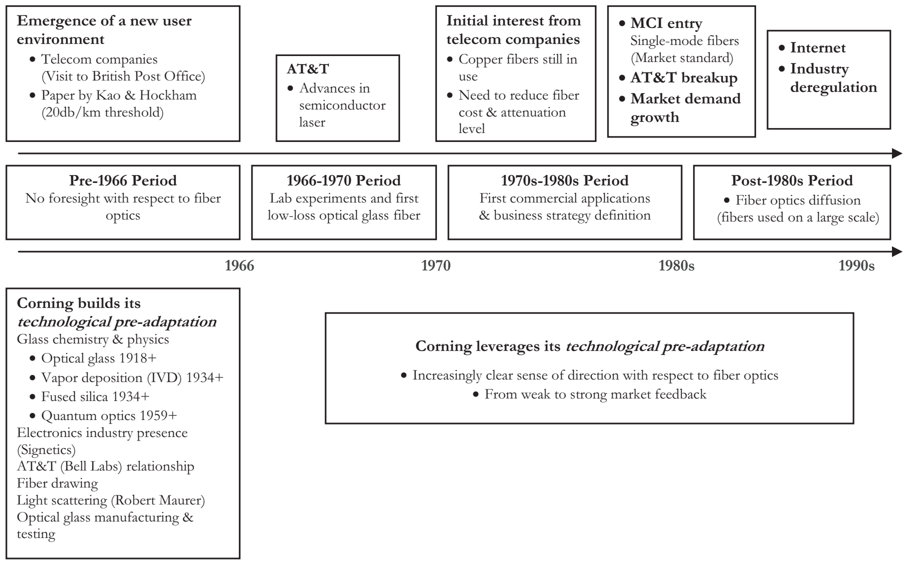

Figure 1 Phases in technological speciation.

emerges, as the Corning case illustrates. However, the logic underlying other types of options whereby an initial upfront investment is deliberately made to achieve a specific end, such as an option to grow, does not fully apply to our notion of technological pre-adaptation.

Pre-adaptation implies that success in a market is determined largely by circumstances established before anyone knew the market would exist. This implies that only knowledge accumulated before 1966 represents pre-adaptation for later stages. After 1966, the paper by Kao and Hockham fostered the first wave of laboratory experiments to meet the 20 db/km threshold and the BPO's interest in replacing copper fibers with optical glass fibers signaled the existence of a potentially profitable market. As a result of these changes in the environment, the value of pre-existing technological knowledge in the new application became apparent.

Thus, year 1966 is an ideal dividing line between the period when foresight was not a factor and the period when a higher level of foresight was more explicitly at work. This line marks the transition from the phase when firms accumulate the pre-adaptation to the phase when they actually leverage it into a new domain, implying deliberate effort. The evolution of technology is clearly continuous; any attempt at breaking it into phases is obviously arbitrary. Nevertheless, year 1966 did mark a turning point in the development of fiber optics. This applied not only to Corning but to the industry as a whole, as our interviews and archival data confirmed.

Between 1966 and 1970, Corning began to leverage its technological knowledge base in the development of fiber optics. It conducted the first laboratory experiments as it recognized its emerging opportunity and capitalized upon prior experience by forming a dedicated research team. It put optical fibers on a list of potential projects for graduate students during 1967 and continued the projects in the following years. Corning had to satisfy the needs of long-distance telecom companies and produce fibers with very low attenuation levels. These needs and required performance standards defined the selection criteria characterizing the nascent fiber optics market. This is the phase in which we observed the convergence between a firm's technological knowledge base and a new user environment.

During this period, higher levels of foresight presumably guided firms' R&D and important strategic decisions were made. Despite the uncertainty that usually surrounds this phase, good strategy "is not necessarily enacted with a high level of initial confidence, although general management may appear confident in order to spur action. If firms wait until the proper method of entering a market or producing a product is fully understood, it will normally be too late to take advantage of the information" (Rumelt, 1984: 569).

While we emphasized pre-adaptation, we do not downplay the significance of purposive behavior in the search for new technologies. The extent to which firms leverage prior experience once the environment presents them with a new investment opportunity reflects purposive behavior. We can therefore observe heterogeneity even among firms with similar levels of technological pre-adaptation. The same body of knowledge can generate a range of possible paths to pursue, although it means that managers have to gamble on which path to pick, because there is no certain "right" path to success (Helfat and Raubitschek, 2000: 968).

A very interesting case, in this regard, is American Optical Company (AOC). During the 1950's, it contributed to the development of the fiberscope, an image-transmitting device that used the first practical all-glass fiber, primarily employed for medical applications (e.g., endoscope). It tested a fiber optic endoscope on a patient for the first time in 1957. AOC has been active in the production of this type of glass fibers for many years and is still a prominent player in the medical sector. Its patents have been widely cited by subsequent patents in fiber optics for communication applications. In the three-key patents with which Corning laid out the practical implementation of fiber optics, several cited patents were filed by AOC. The same holds true for patents that Corning and other firms filed afterward. AOC was then potentially pre-adapted, although it never entered the telecommunications market. This suggests that firms endowed with relevant transferable knowledge may or may not re-deploy it into a new domain, whether they recognize a new investment opportunity but decide not to take advantage of it or even if they do not recognize that opportunity (oversight).

A different case is that of AT&T and ITT. Despite its monopoly within the long-distance telecommunications industry and being among the first to enter the new market, AT&T failed to take the lead in the development of fiber optics and lost the advantage to Corning. Several factors might account for this outcome. For Corning, which at the time was looking for new investment opportunities to counter a declining performance in some of its traditional businesses, fiber optics was seen from the very beginning as a technology that could open up a new market with a high growth potential. For AT&T, on the contrary, it was largely a substitute technology bound to replace an existing telecommunications network in which traditional copper-based technologies were still in use—during the 1970s, AT&T continued to invest in copper fibers to renew its telephone network. As a result, while it was interested in optical glass fibers, AT&T's immediate goal was to recover first these investments before switching to fiber optics. The incentive to invest in the new technology and accelerate its large-scale adoption was obviously quite different than for Corning.

Based on Kao's and Hockham's work, ITT filed a patent in the UK in 1967 that was issued eighteen months later. However, ITT never filed the same patent anywhere else and, when the first tax or maintenance payment was due on the patent, it did not pay for it, and the patent lapsed into obscurity.[10] Although its engineers had done most of the theoretical groundwork for fiber optics, ITT—which, at the time, was one of the largest US-based conglomerates—concentrated not on fibers, whose production was outsourced, but on cabling. Equally pre-adapted firms can thus differ with respect to the ability to leverage their technological knowledge base when they recognize a new opportunity. But they also differ with respect to when and/or how quickly they do so.

After Corning demonstrated the commercial feasibility of fiber optics in 1970, market feedback became increasingly clear and provided more explicit direction as to future development. During this period, Corning experimented with the new technology in pilot plants and conducted several field experiments to more fully understand the properties of the materials used in the production of fibers, perfect their quality, and lower production costs. Thanks to its level of technological pre-adaptation, Corning clearly had a head start in implementing the new technology. During the time when most of the early sales consisted of samples of fibers sold to telephone companies willing to test their potential, Corning learned a great deal from these applications. Capitalizing on its glass experience and the sets of experiments conducted over this period, it moved along the learning curve faster than most of its competitors. Especially in the case of complex new technologies, there are essential aspects of learning that are a function of the experience accumulated in the process of not only producing the product that embodies those technologies but also using that product. Rosenberg's (1982: 122) distinction between learning by doing and learning by using is, therefore, very important in explaining how Corning stayed ahead of competition.

Despite its advantage in terms of technological pre-adaptation, Corning was not equally well equipped to successfully compete in a market (telecommunications) in which it had never before operated. Corning thus tried to develop a viable business

[10]We thank Alfred L. Michelson, former head of the patent department at Corning, for providing us with this piece of information.

mainly by concentrating its R&D on constantly improving optical fiber products and production processes (Teece *et al.*, 1997), adopting an aggressive property rights strategy as a key isolating mechanism (Rumelt, 1984), and creating complementary assets, often by forming partnerships with other companies (Teece, 1986).

The last period coincides with the emergence of a large and profitable market for fiber optics in the United States, as confirmed by the number of firms that entered the market. It is during the early 1980s that we truly observe a "tipping point" (Gladwell, 2000) in the evolution of fiber optics: with MCI's first large order and AT&T's breakup, market demand, in addition to sales and profits, registered an explosive growth. Corning and its competitors significantly increased their R&D effort to improve fibers and reduce their cost. MCI's decision, and the ensuing adoption of a new standard (i.e., single-mode fibers), exemplifies how market feedback can shape the direction of R&D. This is consistent with a demand-based perspective on technological evolution (e.g., Schmookler, 1966; von Hippel, 1988; Adner, 2002) and its emphasis on the critical role that end users can play in defining new selection criteria (or performance standards) and creating new market opportunities.

A closer look at the last two periods sheds light on how a new technological lineage can originate from re-deploying existing technological knowledge into a different domain. After the convergence between its technological knowledge base and the new user environment, Corning began to take specific actions to satisfy the users' needs and performance requirements of the fiber optics market. New patterns of internal resource allocation emerged which mirrored the relative importance of the new business as compared to other businesses. Over the years, Corning's telecommunications business grew from being almost non-existent back in 1970 (Table 2) to dominating the market. Thus, the nature of the selection forces in the new application domain not only influences the chance that technological speciation occurs but also the pace at which it unfolds.

6. Conclusions

The dynamics of technological speciation are complex. Firms often select new technological trajectories on the basis of how well their stock of knowledge matches the requirements of novel applications. It is difficult to explain a firm's behavior by simply looking at its stock of knowledge, because it is unclear how widely this stock can be used. From a normative perspective, firms should perhaps spend less time trying to forecast new areas of application for which they create new knowledge and, instead, scan areas in which their existing knowledge better fits (e.g., Denrell, Fang, and Winter, 2003). Firms with a long-standing tradition in R&D already might have in-house solutions to problems that materialize in a more distant future (Garud and Nayyar, 1994).

A central assumption in evolutionary theory is that firms typically search locally within the boundaries of their existing knowledge domain (e.g., Nelson and Winter, 1982; Helfat, 1994). However, some firms display a higher propensity to search beyond such boundaries (e.g., Rosenkopf and Nerkar, 2001). As research on learning has taught us, firms have "to cope with confusing experience and the complicated problem of balancing the competing goals of developing new knowledge (i.e., exploration) and exploiting current competencies in the face of dynamic tendencies to emphasize one or the other" (Levinthal and March 1993: 95). The dynamics of technological speciation shows that the two processes can co-exist. As firms seek to exploit their base of experience in a new domain, they must learn how to satisfy new market needs and performance standards, and then engage in exploration. Moreover, as they accumulate absorptive capacity (Cohen and Levinthal, 1990) or assets (Dierickx and Cool, 1989), especially knowledge-based assets such as a new technology, in that domain, firms are also likely to expand their level of technological pre-adaptation with respect to new, yet unanticipated, applications.

We believe that this study contributes to extant research on industry dynamics showing how prior experience positively affects new market entry decisions, firm performance, and the evolution of market structure, especially when firms leverage their prior experience in a different domain than the one in which it was originally accumulated (e.g., Carroll *et al*., 1996; Klepper and Simons, 2000; Helfat and Lieberman, 2002; Klepper, 2002). This stream of research has enhanced significantly our understanding of the relation between prior experience, firm innovation, and performance. What is not entirely clear in these studies is whether firms innovate, because they anticipate which knowledge will be required or the environment selects those firms whose knowledge randomly matches the requirements of a new domain. Identifying the "watershed event" that separates the pre-adaptation phase from one of strategic intention helped us address this question and delineate the role for strategy more accurately.

An important implication of studying technological speciation at the firm level is to further enhance our understanding of how technological evolution occurs. We began the paper by emphasizing how models of technological evolution generally describe the technology life cycle as characterized by periods of incremental innovation that are punctuated by sudden bursts of radical innovations (Abernathy and Utterback, 1978; Tushman and Romanelli, 1985; Tushman and Anderson, 1986; Anderson and Tushman, 1990; Mokyr, 1990). Punctuated equilibrium models offer a very powerful description of a pattern frequently observed in the evolution of technology. However, they typically lack accurate knowledge of the micro-level causal mechanisms that might produce those patterns. Since punctuated equilibrium theory is essentially a theory of speciation (e.g., Eldredge and Gould, 1972; Gould and Eldredge, 1977), we believe that our analysis of the dynamics of technological speciation sheds light on the microprocesses and evolutionary forces underlying the emergence of a new technology. In this sense, the use of longitudinal case studies adopting a process-oriented view might fruitfully complement large sample studies that investigate the same phenomenon but at a different level of analysis.

Moreover, since we examined technological speciation at the firm level and traced the microprocesses that led to the emergence of fiber optics, our study provides additional evidence on the continuity underlying technological change. The belief that certain innovations stem from revolutionary upheavals in technology often reflects the concealment of crucial antecedents (Basalla, 1988). This tendency to stress departure from the past and over-emphasize elements of novelty is exacerbated by successful innovators' *ex post* rationalizations and self-congratulations. As Basalla (1988: 30) puts it, " . . . key artifacts – such as the steam engine, the cotton gin, or the transistor . . . illustrate the evolutionary hypothesis despite the fact that initially they appear to be excellent candidates for use in supporting the contrary discontinuous explanation." The longitudinal character of this study helped us avoid some of these pitfalls, as we could identify fairly accurately some crucial antecedents that shaped the emergence and growth of fiber optics technology. Since fiber optics grew largely out of Corning's expertise in specialty glass, our study not only illustrates some of the crucial antecedents that precede breakthrough innovations, it also shows how *revolutionary* outcomes often originate from *evolutionary* strands that involve no break from the past (Garud *et al.*, 1997). A seemingly radical technological change might actually reflect the novelty of the new selection environment in which a firm re-deploys its knowledge rather than perform a discrete shift in its technological knowledge base.

This article suffers from obvious limitations. In particular, it is questionable whether our findings can be generalized. Although additional evidence is needed to verify how general the processes actually are, we believe an in-depth historical study to be well suited to provide richer contextual evidence and a finer description of the micro-level processes and organizational factors shaping the development of a new technology. Moreover, identifying a clear dividing line to distinguish between distinct evolutionary phases and underlying processes as we did in this study might not be always feasible. One could even question the possibility of identifying such a dividing line on the grounds that it defies our previous claim that technological evolution is continuous. However, we see this as a necessary, yet reasonable, compromise to establish as accurately as possible when new evolutionary patterns emerge and trace their evolution over time. Future research might find this a worthwhile issue to investigate further.

Acknowledgements

Funds for this research project were provided by the Mack Center for Technological Innovation at Wharton. We gratefully acknowledge helpful comments on earlier drafts of the paper from Christina Fang, Moshe Farjoun, Simone Ferriani, Constance Helfat, Witold Henisz, Daniel Levinthal, Johannes Pennings, Claus Rerup, and the participants of the 2001 Academy of Management Conference, Washington, and of the 2002 CCC Doctoral Consortium, Boston. We thank Genever McBain for her assistance in editing the article. Special thanks go to Sidney Winter for his insight and help at various stages in the development of the article, and John Lafkas and Joe Porac, whose thoughtful critiques helped to polish the final draft. We are also particularly grateful to Tom MacAvoy (Corning), whose comments and feedback proved critical for a correct understanding of the events and the technical issues described in the article, Donald B. Keck (Corning), Alfred Michelson (Corning), Stuart Sammis (Corning). All errors are the author's responsibility.

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