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Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change

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An evolutionary model of technological change is proposed in which a technological breakthrough, or discontinuity, initiates an era of intense technical variation and selection, culminating in a single dominant design. This era of ferment is followed by a period of incremental technical progress, which may be broken by a subsequent technological discontinuity. A longitudinal study of the cement (1888–1980), glass (1893–1980), and minicomputer (1958–1982) industries indicates that when patents are not a significant factor, a technological discontinuity is generally followed by a single standard. Across these diverse product classes, sales always peak after a dominant design emerges. Discontinuities never become dominant designs, and dominant designs lag behind the industry's technical frontier. Both the length of the era of ferment and the type of firm inaugurating a standard are contingent on how the discontinuity affects existing competences. Eras of ferment account for the majority of observed technical progress across these three industries.

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Since the pioneering work of Schumpeter (1934, 1942) and Marx (1906), research has concentrated on the effects of technological change on industries (e.g., Brittain and Freeman, 1980; Astley, 1985; Barnett, 1990), organizations (e.g., Chandler, 1977; Burkhardt and Brass, 1990; Henderson and Clark, 1990), and individuals and roles (Karasek, 1979; Noble, 1984; Barley, 1990). While there has been much literature on the effects of technology on organizations, there has been much less sustained work on the nature and dynamics of technological change (Tushman and Nelson, 1990).

This paper builds on a diverse technology literature in developing and empirically testing a cyclical model of technological change. Technological discontinuities (innovations that dramatically advance an industry's price vs. performance frontier) trigger a period of ferment that is closed by the emergence of a dominant design. A period of incremental technical change then follows, which is, in turn, broken by the next technological discontinuity. We empirically explore when and how dominant designs emerge from technological discontinuities and which firms pioneer dominant designs. This cyclical model of technological change focuses on the social and organizational selection processes that affect the closing on a dominant design and contrasts social and technological dynamics during eras of ferment with those in eras of incremental change.

A CYCLICAL MODEL OF TECHNOLOGICAL CHANGE

While there is a scarcity of models for understanding technological change, research from multiple disciplines suggests several themes that help get inside the black box of technological change (Rosenberg, 1982). Basalla's (1988) comprehensive review of technological evolution was anchored in the concepts of diversity, continuity, novelty, and selection. He reviewed the evolution of the wheel, steam engine, automobiles, and other human artifacts, focusing on diversity driven by random technological breakthroughs followed by selection processes that operate to choose specific artifacts

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for replication. Using a similar evolutionary metaphor, Pinch and Bijker (1987) described the evolution of bicycles from more than ten incompatible forms to convergence on the safety bicycle as the industry standard (two low wheels, rear chain, and air tires). This evolutionary approach of technical variation, selection of an industry standard, and retention via incremental technical change that elaborates and extends the standard has also been echoed in the theoretical work of Nelson and Winter (1982) and the empirical work of Van den Belt and Rip (1987) in the synthetic dye industry.

Research by David (1985, 1987) and Hughes (1983, 1987) in the typewriter, computer, and electric power product classes, Abernathy's (1978) work in the automobile industry, and Sahal's (1981) more general review of technological progress also described periods of technical variation that are closed by the emergence of dominant designs or industry standards. David (1987) and Hughes (1987) focused on the technical, political, and organizational dynamics that drive industry standards and the consequences of these standards for subsequent technological, industrial, and organizational evolution. Jenkins's (1975) research in the photographic industry explored both how product class standards emerged and how wave after wave of technological breakthroughs made existing standards obsolete and opened the industry to successive dominant designs.

Finally, work in the sociology of technology has modeled technological change as evolving through long periods of incremental change punctuated by revolutionary breakthroughs (Constant, 1980, 1987; Landau, 1984; Tushman and Anderson, 1986). This research conceptualizes technology as a set of interdependent and hierarchical systems developed by interlinked communities of practitioners. As technology evolves through periods of incremental, puzzle-solving progress, practitioners become more interdependent and develop ever deeper and more inertial competence bases (Henderson and Clark, 1990). Building on Kuhn's (1962) work in science, this research focuses on the response of inertial communities of practitioners and organizations to competence-destroying or competence-enhancing technological discontinuities (Landau, 1984; Barley, 1986).

These disparate research streams suggest that technological change can be fruitfully characterized as a sociocultural evolutionary process of variation, selection, and retention (Campbell, 1969). Variation is driven by stochastic technological breakthroughs. Technological discontinuities initiate substantial technological rivalry between alternative technological regimes. Social, political, and organizational dynamics select single industry standards or dominant designs from among technological opportunities. Positively selected variants then evolve through relatively long retention periods, marked by incremental technical change and increased interdependence and enhanced competence within and between the communities of practitioners. Periods of incremental technical change may be broken by subsequent technological breakthroughs (e.g., Jenkins, 1975; Landes, 1983). Technological advance may, then, be driven by the combination of chance or random events (variation), the direct social, political action of individuals and organizations in selecting between rival industry standards (selection), and the incremental, competence-enhancing, puzzle-solving actions of many organizations that are learning by doing (retention).

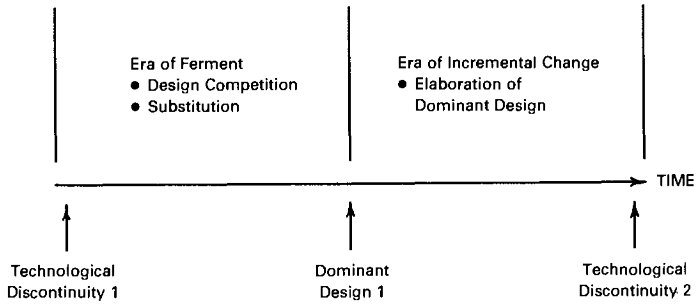
This paper builds on these sociocultural evolutionary ideas. Tushman and Anderson (1986) highlighted a powerful source of variation by demonstrating that the core technology of an industry evolves through long periods of incremental change punctuated by technological discontinuities. These discontinuities predictably affected environmental uncertainty, munificence, and organizational growth rates. This paper extends that work by exploring the other key punctuating event in the evolution of a technology: the emergence of a dominant design after a technological discontinuity. We argue that a breakthrough innovation inaugurates an era of ferment in which competition among variations of the original breakthrough culminates in the selection of a single dominant configuration of the new technology. Successful variations are preserved by the incremental evolution of this standard architecture until a new discontinuous advance initiates a new cycle of variation, selection, and retention. Figure 1 illustrates the components of a technology cycle. The key punctuation points are technological discontinuities and dominant designs; these delimit eras of ferment and eras of incremental change.

We examine each element of this technology cycle with particular reference to the minicomputer, glass, and cement industries. For the purposes of a study like ours, technology could be examined at several levels of analysis. For instance, we could have examined the evolution of milk bottles, glass containers in general, or packaging. In this study, the technology of an industry was defined by its four-digit Standard Industrial Classification (SIC) code to use standard industry boundaries.

Technological Discontinuities

At rare and irregular intervals in every industry, innovations appear that "command a decisive cost or quality advantage and that strike not at the margins of the profits and the outputs of the existing firms, but at their foundations and their very lives" (Schumpeter, 1942: 84). Such innovations depart dramatically from the norm of continuous incremental innovation that characterizes product classes, and they may be termed technological discontinuities. These discontinuities either affect underlying processes or the products themselves.

Figure 1. The technology cycle.



Process discontinuities are fundamentally different ways of making a product that are reflected in order-of-magnitude improvements in the cost or quality of the product. They include the Bessemer furnace in steel production, catalytic cracking of petroleum, electronic imaging (vs. light-lens copying), genetic engineering using restriction enzymes, and dry gelatin photographic processes. Product discontinuities are fundamentally different product forms that command a decisive cost, performance, or quality advantage over prior product forms. Product discontinuities include jet (vs. piston) engines, diesel (vs. steam) locomotives, electronic (vs. mechanical) typing, quartz (vs. mechanical) movements in watches, CT scanners (vs. x-rays), or integrated circuits (vs. discrete transistors) (Tushman and Anderson, 1986).

A brief history of the flat-glass industry illustrates how an industry is revolutionized at rare intervals by discontinuous advance (see Table 2 for the data sources used). When window glass manufacture began in America, the dominant process was hand cylinder blowing. A highly skilled artisan, with the help of several assistants, blew a gob of molten glass into a large cylinder, which the assistants cut with a hot wire and flattened with irons into panes. In 1857, the first U.S. plate glass factory was established, bringing to this country the European process of rolling a glass sheet on a table, then polishing it until the two surfaces were parallel. Due to differences in cost and quality, plate and window glass manufacture remained separate industries.

In 1903, J. H. Lubbers of American Window Glass perfected a machine that could blow glass cylinders rapidly and inexpensively. The Lubbers machine displaced the skilled handblower, revolutionizing window glass production. Yet American Window Glass kept its process proprietary, encouraging other inventors to find even more efficient means of producing sheet glass. In 1917, the Colburn process for drawing a continuous ribbon from a tank of molten glass was introduced commercially. This continuous process outmoded the Lubbers machine, and within 12 years, cylinder blowing machines had virtually disappeared. Continuous drawing was introduced in the plate glass industry in 1923, with similar results. Finally, decades of research culminated in the development of the float-glass process at Pilkington, a British glassmaker. Molten glass was passed across a bath of molten alloy; the production rate increased dramatically, since the ribbon was subject to less resistance in drawing. Additionally, the ribbon emerged perfectly flat, eliminating the need for grinding and causing the window and plate glass industries to converge into a single SIC code.

The Lubbers machine, the Colburn process, continuously drawn plate glass, and float glass are archetypal technological discontinuities. Tushman and Anderson (1986) defined a technological discontinuity as an order-of-magnitude improvement in the maximum achievable price vs. performance frontier of an industry. They demonstrated that technological change within a product class consists of long periods of incremental change punctuated by discontinuities. The evolution of flat-glass technology illustrates the way each breakthrough creates a technological order, a dominant way of making sheet glass that arises from a dramatic breakthrough and which, once established, evolves incrementally until the next discontinuous advance overthrows it, in turn.

Figure 2a depicts progress in the flat-glass industry, defined in this case as the capacity of a machine in square feet per hour. Note that each discontinuity dramatically advances the performance frontier of the industry. Figure 2b depicts progress in capacity (bottles per minute) of container-glass machines. The vertical axis represents the capacity of the state-of-the-art machine in a given year t, divided by the capacity of the state-of-the-art machine in year t-1. For instance, in Figure 2a, an artisan blowing cylinders by hand could produce 150 square feet per hour of sheet glass; a 1903 Lubbers machine increased the maximum achievable production rate to 700 square feet per hour. An improved version of the Lubbers machine introduced in 1907 moved the frontier to 800 square feet per hour; the state of the art reached 1,160 square feet per hour with the introduction of the Colburn machine. The first float-glass machines increased the capacity to 5,700 square feet per hour, and later models eventually reached 17,600 square feet per hour with subsequent increases in scale.

Figure 2a. Technological progress of machines in the U.S. flat-glass industry, in square feet per hour.

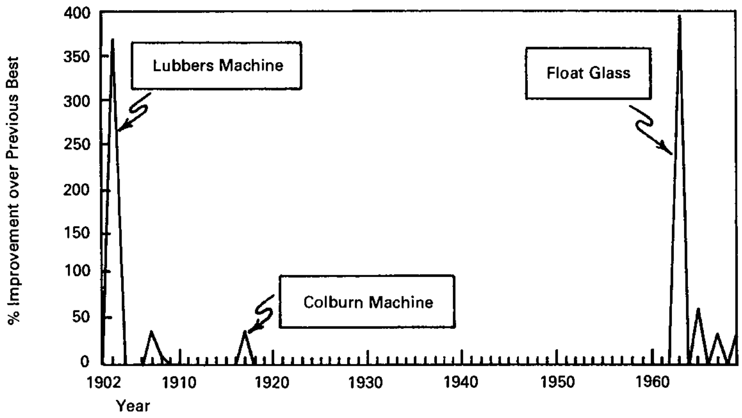
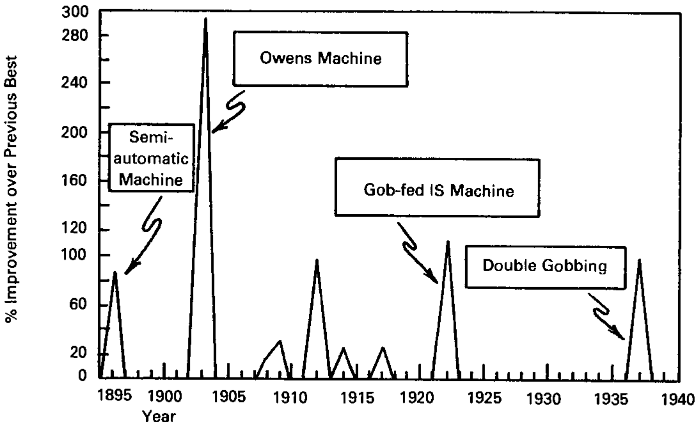


Figure 2b. Technological progress of machines in the U.S. container-glass industry, in bottles per minute.



Figures 2a and 2b graphically illustrate these periods of incremental technical improvement, punctuated by discontinuous advances, yet some improvements are not discontinuities. There are peaks in both figures, representing advances in the performance frontier that advance the state of the art (sometimes considerably) but that represent evolutionary rather than revolutionary technical advances. A discontinuity not only moves forward the state of the art; it also represents a new way of making something or a new fundamental product architecture. For instance, Figure 2a shows that although the float-glass process was improved over time, subsequent improvements of float glass did not change the basic glass-making process; they were principally scaled-up versions of the original float-glass plants with some added enhancements. Figure 2b shows that the breakthrough 1903 Owens machine (the first automated bottle maker) was improved in 1908, 1909, 1912, 1914, and 1917, with each improvement advancing the state of the art. These advances were refinements of the fundamental Owens design; the original six-armed machine was supplemented by 10-arm and 15-arm versions embodying the same principles as the 1903 design. It is the replacement of hand-blowing with machine-blowing, of batch cylinder production with continuous-ribbon production, of drawing with float glass, and of the Owens machine with the gob feeder that creates a new technical order and significantly advances the industry's performance frontier, therefore constituting technological discontinuities. Following Schumpeter, we focus on new products and processes that strike at the very foundation of the existing technical order.

Tushman and Anderson (1986) further characterized technological discontinuities as competence-enhancing or competence-destroying. A competence-destroying discontinuity renders obsolete the expertise required to master the technology that it replaces. For example, the skills of mechanical watch manufacturers or vacuum-tube producers were rendered irrelevant by quartz watches and integrated circuits, respectively. Similarly, the skills of the glass-making artisan were made obsolete by the Lubbers machine, which allowed unskilled operators to make glass cylinders. Knowing how to make and flatten cylinders contributed little to knowing how to draw a continuous ribbon of glass from a tank. Drawing-machine know-how, in turn, did not translate to the float-glass process, which critically depends on understanding properties of the alloy bath.

A competence-enhancing discontinuity builds on know-how embodied in the technology that it replaces. For example, the turbofan advance in jet engines built on prior jet competence, and the series of breakthrough advancements in mechanical watch escapements built on prior mechanical competence. Similarly, the Edison cement kiln allowed cement makers to employ their existing rotary-kiln knowledge to make much greater quantities of cement. Later, retrofitting of process controls to cement kilns again allowed manufacturers to build on accumulated know-how while dramatically accelerating production through minute control of the process. These competence-enhancing innovations introduce a new technical order, with a vastly enhanced performance frontier, while

Table 1

Descriptive Statistics on Sixteen Technological Discontinuities in Three Industries

(1) Discontinuity	(2) Year introduced	(3) Effect on competence	(4) Industry standard
Cement			
Continuous vertical kiln	1888	Enhancing	None
Rotary kiln	1892	Destroying	6 × 60 ft. kiln Hurry-Seaman
Edison long rotary kiln	1903	Enhancing	120–125 ft. kiln
Computerized long kiln	1960	Enhancing	500–580 ft. kiln
Suspension preheating	1972	Destroying	4-stage cyclone, flash calciner
Container glass			
Semiautomatic machinery	1893	Destroying	United Machine
Owens machine	1903	Destroying	AN/AR Series
Gob-fed machinery	1915	Enhancing	IS Model C
Double gobbing	1937	Enhancing	5-section Model E
Flat glass			
Machine cylinder	1903	Enhancing	Improved Lubbers
Drawing machines	1917	Destroying	Fourcault machine
Continuous forming	1923	Destroying	None
Float glass	1963	Destroying	None
Minicomputers			
Solid-state circuits	1960	Destroying	None
Integrated circuits	1965	Destroying	16-bit machine, core memory
Semiconductor memory	1971	Enhancing	16-bit machine, 16K MOS memory

* Performance expressed in the following units: Cement: barrels/day kiln capacity; Container glass: bottles/minute machine capacity; Flat glass: square feet/hour machine capacity; and Minicomputers: microseconds/CPU cycle.

building on the existing technical order rather than making it obsolete.

Table 1 lists the sixteen technological discontinuities examined in this study and indicates which are competence-enhancing and which are competence-destroying, whether each culminated in a dominant design, how long it took the dominant design to emerge, and when sales of all versions of the new technology peaked. The methods section and the Appendix describe in greater detail how discontinuities were identified and how they affected existing competence. Each discontinuity inaugurates a technology cycle, which begins with an era of ferment following the introduction of a breakthrough innovation.

Era of Ferment

The introduction of a radical advance increases variation in a product class. A revolutionary innovation is crude and experimental when introduced, but it ushers in an era of experi-

Table 1 (*continued*)

(5) Year standard achieves 50%	(6) Time to standard	(7) Year new sales peak	(8) Performance of dominant design	(9) Performance frontier*
		Cement		
–	–	–	–	–
1900	8 years	1906	375	400
1910	7 years	1911	833	2,500
1965	5 years	1966	12,000	12,000
1979	7 years	1981	17,750	20,000
		Container glass		
1908	15 years	1910	6.5	15
1915	12 years	1917	40	50
1927	12 years	1930	125	135
1948	11 years	1956	250	270
		Flat glass		
1911	8 years	1915	800	800
1937	20 years	1940	1000	1160
–	–	–	–	–
–	–	–	–	–
		Minicomputers		
–	–	–	–	–
1970	5 years	1972	.96	.75
1976	5 years	1978	.30	.24

mentation as organizations struggle to absorb (or destroy) the innovative technology. This era of ferment is characterized by two distinct selection processes: competition between technical regimes and competition within the new technical regime. This period of substantial product-class variation and, in turn, uncertainty ends with the emergence of a dominant design.

Older technological orders seldom vanish quietly; competition between old and new technologies is fierce (Foster, 1986). New technologies are disparaged when they are introduced because they frequently do not work well and are based on unproven assumptions and on competence that is inconsistent with the established technological order (Schön, 1971; Jenkins, 1975). The response of the existing community of practitioners is often to increase the innovativeness and efficiency of the existing technological order. For example, mechanical typewriters, piston jets, telegraphy, gas lighting, mechanical watches, and sailing ships all experienced sharp performance advances in response to technological threat (Bright, 1949; Cooper and Schendel, 1976; Hughes, 1983; Landes, 1983).

While discontinuous technological advance does not always dominate older technical orders (e.g., bubble memory, wankel engines, tuning-fork oscillation, or the ALCOA smelting process for aluminum), research on technical substitution has shown that substitution follows a classic logistic curve (Rogers, 1982; Waterson, 1984). Fisher and Pry (1971) found that substitution does not immediately follow the appearance of a radical innovation but that the eventual supplanting of a new technology is rapid once the superiority of the new technology is established.

Concurrent with competition between technical orders is the process of design competition within a technological order. Several versions of the breakthrough technology appear, both because the technology is not well understood and because each pioneering firm has an incentive to differentiate its variant from rivals'. Crude initial designs rapidly improve (Abernathy, 1978). For example, in power generation, AC systems competed with DC systems, and even within AC systems there was competition among alternative frequencies (125, 100, 120, 40, 60 cycles per second) (Hughes, 1983; David, 1987). Quite apart from competition between tuning-fork, quartz, and mechanical escapement for watch oscillation, there was competition within each technical order between rival approaches (Landes, 1983). Similarly, once the first personal computer appeared in 1976, it was followed by a host of different models with different (and incompatible) microprocessors, disk formats, and operating systems (Freiberger and Swaine, 1984). In 1990, three incompatible design approaches characterize technical development in high-definition television (HDTV).

During the era of ferment, variation and selection pressures are substantial due to both substitution and design competition. We therefore hypothesize that product-class ferment will be characterized by a high rate of variation, reflected in the number of variants of old and new technology competing in the market:

Hypothesis 1: The mean number of new designs introduced during the era of ferment is greater than during the subsequent era of incremental change.

The length of the era of ferment may be contingent on the type of technological discontinuity. When a technology builds on a completely new knowledge base, many rival designs appear, and it will take longer for market forces to sort out these variants than it will when technical change is competence-enhancing. Similarly, firms confronted with the choice of abandoning existing know-how in the face of competence-destroying technical change will defend older technology more stubbornly, prolonging uncertainty about whether the new technology will become dominant. The process of converging on a standard is hampered by a lack of common understanding among technical experts about how the new technology operates and where its economic performance limits lie. Thus, we hypothesize:

Hypothesis 2a: The era of ferment following a competence-destroying discontinuity is longer than the era of ferment following a competence-enhancing discontinuity.

When a breakthrough innovation builds on existing know-how, the era of ferment is relatively short. We argue, further, that this effect is cumulative. A series of major advances may all enhance an established body of know-how. In each successive instance, the technology is increasingly well understood and institutionalized (e.g., Constant, 1980). Only when a competence-destroying discontinuity breaks the mold is this cumulation of competence interrupted:

Hypothesis 2b: The era of ferment grows shorter in each of a series of consecutive competence-enhancing discontinuities.

Dominant Designs

For variation and selection to cumulate in an evolutionary process, there must be a retention mechanism; a successful variation must be preserved and propagated (Campbell, 1969). A dominant design is the second watershed event in a technology cycle, marking the end of the era of ferment. A dominant design is a single architecture that establishes dominance in a product class (Abernathy, 1978; Sahal, 1981). Once a dominant design emerges, future technological progress consists of incremental improvements elaborating the standard and the technological regime becomes more orderly as one design becomes its standard expression. For example, in the early automobile and airplane industries, technological variation between fundamentally different product designs (e.g., gas, steam, and battery-powered engines) remained high until industry standards emerged to usher in periods of incremental change elaborating the standards (i.e., the internal combustion engine, open automobile, and the DC-3 airplane) (Miller and Sawers, 1968; Abernathy, 1978).

A number of scholars have incorporated dominant designs into models of technological evolution. Utterback and Abernathy (1975) suggested that the emergence of a dominant design is the key event in the evolution of an industry, marking the transition from a fluid to a specific state. Clark (1985) and Henderson and Clark (1990) supported and extended these ideas. Dosi (1984) followed Nelson and Winter's (1982) idea that technologies evolve according to natural trajectories, arguing that these trajectories are shaped by technological paradigms. Normal technological activity consists of progress along a trajectory defined by this paradigm; extraordinary innovations overthrow the paradigm (Kuhn, 1962). Sahal (1981) argued that certain designs, called technological guideposts, set a pattern for subsequent technological progress and that once a technological guidepost is established, innovation proceeds by incremental modification of the basic design.

Dominant designs emerge across diverse product classes. Whether in sewing machines or rifles (Houndshell, 1984), bicycles (Bijker, Hughes, and Pinch, 1987), synthetic dyes (van den Belt and Rip, 1987), machine tools (Noble, 1984), reprographic machines (Dessauer, 1971), or photolithography (Henderson and Clark, 1990), single designs emerge to dominate rival designs. These designs remain dominant until the next technological discontinuity. While only known in retrospect, dominant designs reduce variation and, in turn, uncertainty in the product class.

Dominant designs permit firms to design standardized and interchangeable parts and to optimize organizational processes for volume and efficiency (Abernathy, 1978; Houndshell, 1984). They permit more stable and reliable relations with suppliers, vendors, and customers. From the customer's perspective, dominant designs reduce product-class confusion and promise dramatic decreases in product cost. Finally, if the product or process is part of a larger system, industry standards permit systemwide compatibility and integration (Hughes, 1983; Farrell and Saloner, 1985; David and Bunn, 1988).

Once a design becomes an industry standard, it is difficult to dislodge. Volume production of the dominant design creates economies due to learning by doing (Arrow, 1962; Rosenberg, 1982). Over time, firms cut costs by applying wisdom gained through cumulative experience. As more and more users gain experience with a product, the manufacturer gains a better understanding of maintenance and reliability requirements. Learning by doing depends on the emergence of a dominant design, for until an industry converges on a standard, no design achieves much cumulative production volume.

Dominant designs emerge from each breakthrough innovation as manufacturers, suppliers, customers, and regulatory agencies compete to decrease the uncertainty associated with variation during the era of ferment. There are several alternative selection possibilities. Market dominance might pass back and forth among rival designs over time; one might achieve temporary ascendance only to be supplanted by a competing design, which it might again overtake. Second, several rival designs might achieve stable and roughly equal market shares. Though one might account for a higher percentage, neither could be said to be dominant. The most strict selection mode is one in which one design emerges that accounts, over time, for over 50 percent of new implementations of the breakthrough technology. Only one design can meet this criterion.

When the competition process is artificially forestalled, dominant designs may not emerge. Such cases arise under regimes of high appropriability where a firm is able to build a thicket of patents around a technology and control its diffusion via strategic licensing decisions (Teece, 1986). In such regimes, the innovator is able to appropriate most of the innovation returns. In regimes of low appropriability, rivals appropriate some of these returns via imitation. When significant intellectual property protection exists, the emergence of a dominant design is a matter of strategic choice for the innovating firm:

Hypothesis 3: In regimes of low appropriability, a single dominant design will emerge following each technological discontinuity.

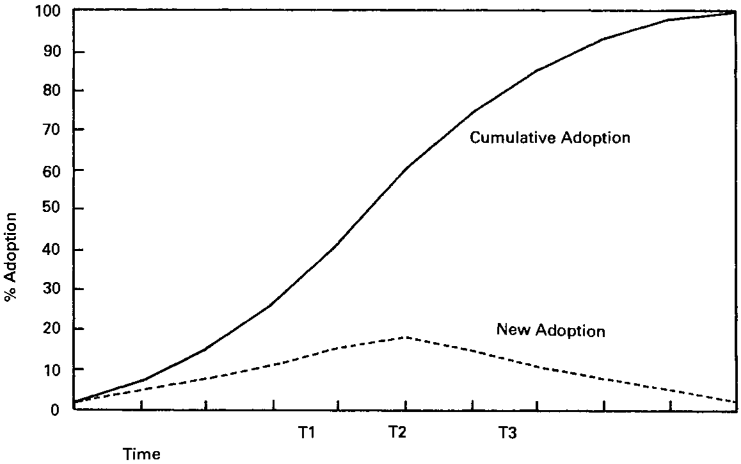
The emergence of a dominant design is directly linked to the diffusion of a new generation of technology. During the era of ferment, potential customers are confronted with several different versions of the new technology. Choosing any variant in the absence of a standard is risky; if another variant becomes the dominant design, the customer must either incur switching costs or forego the benefits of adopting a standard, which typically include scale economies, access to an infrastructure designed around the standard, and so forth. Firms that purchased 12-bit minicomputers in the late 1960s paid a price when 16-bit minicomputers emerged as the dominant design. Semiconductor manufacturers concentrated on 16-bit memory chips, programmers concentrated on 16-bit software, and the price of 16-bit machines dropped at a much faster rate than the price of 12-bit machines, due to volume economies.

The majority of potential adopters will await the emergence of an industry standard before purchasing a new product or installing a new process technology. We argue that the emergence of a standard is a prerequisite to mass adoption and volume production of a new generation of technology. Dominant designs are not simply an artifact of the way in which innovations diffuse. Suppose that a technology diffuses along a classic cumulative logistic curve, so that new adoption in each period of time approximates a normal curve, as shown in Figure 3. T2 represents the point at which sales of the new technology peak. If a dominant design emerged after T2, say at T3, it would only be "dominant" among the population of late adopters: the majority of purchasers would have embraced the new technology during the era of ferment. In such a case, the existence of a dominant design might be an artifact of the tendency of late adopters to focus on cost and select a commodity-like version of the new technology.[1] To the contrary, we suggest that a dominant design will occur at some point such as T1, prior to the sales peak. We contend that the emergence of a dominant design enables sales to take off, not that the eventual decline of sales signals a dominant design:

Hypothesis 4: After each technological discontinuity, sales of all versions of the new technology will peak after the emergence of a dominant design, not during the era of ferment.

A dominant design emerges in several ways. De facto standards emerge when users prefer one design over others.

Figure 3. Model of dominant design and technology diffusion.



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[1] We thank an anonymous reviewer for pointing out this possibility.

David's (1985) description of the QWERTY typewriter keyboard and the battle between AC and DC power systems indicates that dominant designs emerge from market demand, which is affected by the combination of technological possibilities and individual, organizational, and governmental factors. Similarly, the Apple II personal computer or the VHS format in VCRs were not necessarily the best products of the day (measured purely by technical performance), but they contained a package of features that found favor in the market (Freiberger and Swaine, 1984). Though the DC-3 embodied many ideas previously introduced on other aircraft, it offered a unique combination of features that made it the most popular propeller-driven aircraft of all time (Miller and Sawers, 1968).

Dominant designs may also arise in other ways. The market power of a dominant producer may put enough weight behind a particular design to make it a standard, as in the case of the IBM 370 series mainframe and the IBM personal computer (DeLamarter, 1986) or AT&T's Touchtone standard (Brock, 1981). A powerful user may mandate a standard, as the U.S. Air Force imposed numerical control on the programmable machine-tool industry (Noble, 1984). An industry committee may establish a durable standard, as in the case of computer communications protocols (Farrell and Saloner, 1988) and operating systems (Gabel, 1987), or a group of firms may form an alliance around a standard, as in the case of shared bank-card systems (Phillips, 1987). Government regulation often compels the adoption of standards, as in the case of television standards (Pelkmans and Beuter, 1987); some have suggested that governments may employ standards as specific policy instruments capable of erecting barriers to trade (LeCraw, 1987).

The dominant design that emerges from the period of ferment is the cumulative product of selection among technological variations. First versions of the new technology do not become industry standards, since they are shaped by technical variation in the era of ferment. As such, first versions will not become dominant designs, despite first-mover advantages that may accrue to their sponsors and cost reductions from moving along an experience curve ahead of rivals. Thus we hypothesize:

Hypothesis 5: A technological discontinuity will not itself become a dominant design.

The emergence of dominant designs, unlike technological discontinuities, is not a function of technological determinism; they do not appear because there is one best way to implement a product or process. Rival designs are often technologically superior on one or more key performance dimensions. For example, the IBM PC was not the fastest personal computer, JVC's VHS format did not offer the sharpest videocassette reproduction, and Westinghouse's AC power systems were not the most efficient. Dominant designs may not even be particularly innovative; they often incorporate features pioneered elsewhere (Miller and Sawers, 1968).

If dominant designs do not emerge from inexorable technical logic, how do they evolve? We argue that since a single technological order rarely dominates all other technologies on important dimensions of merit, social or political processes adjudicate among multiple technological possibilities. If the emergence of dominant designs is an outcome of the social or political dynamics of compromise and accommodation between actors of unequal influence, these standards cannot be known in advance. While dominant designs are critical at the product-class level, for a given firm, betting on a particular industry standard involves substantial risk (e.g., Sony's gamble on Betavision technology, RCA's gamble on videodisks, and Sylvania's gamble on the simulcast HDTV design). The concept of dominant design, then, brings technological evolution squarely into the social and organizational realm. Actions of individuals, organizations, and networks of organizations shape dominant designs.

Producers and customers accept a package of relatively well-known innovations and forego the best technical performance in order to reduce technological uncertainty. State-of-the-art designs typically achieve superior performance through experimental, risky advances that may be too unreliable and expensive for the majority of adopters. Since dominant designs reflect a set of technical, social, and political constraints, we expect to find at least one rival that is better than the dominant design in purely technical terms. We therefore hypothesize that dominant designs lie behind the industry performance frontier:

Hypothesis 6: A dominant design will not be located on the frontier of technical performance at the time it becomes dominant.

Tushman and Anderson (1986) found that the locus of innovation for technological discontinuities depends on whether the breakthrough builds on or destroys existing competence. Similarly, when firms use existing know-how as a platform for adopting an innovation they are more likely to pioneer variants that survive design competition in an era of ferment. When, instead, existing firms must abandon existing know-how and acquire a new skill base, they will defend their outmoded technology and lag behind new entrants, who are unburdened by commitments to an old technical regime:

Hypothesis 7: Dominant designs arising from competence-destroying discontinuities will be initiated by new entrants in the industry, while dominant designs arising from competence-enhancing discontinuities will be initiated by firms whose entrance preceded the discontinuity.

Era of Incremental Change

The emergence of a dominant design changes the competitive landscape (Utterback and Abernathy, 1975). New designs must win market share from an entrenched standard that is well understood within the marketplace, whose costs have been driven down an experience curve, and which often benefits from centrality in a network of supporting technologies (Constant, 1987; David and Bunn, 1988). For instance, architectures rivaling the IBM personal computer (based on the Intel 8080 microprocessor and the MS-DOS operating system) generally failed once the IBM standard became established. The standard was entrenched in distribution channels and the mind of the consumer; the price of IBM-compatible machines had been reduced sharply by cumulative experience; and, perhaps most significantly, the vast majority of software and peripherals were specifically engineered for compatibility with the standard. Similarly, once the 60-foot Hurry-Seaman cement kiln became a standard, other production equipment (e.g., grinders, slurry feeding systems) was designed to mesh with this particular device.

After a dominant design emerges, technological progress is driven by numerous incremental innovations (Myers and Marquis, 1969). Variation now takes the form of elaborating the retained dominant design, not challenging the industry standard with new, rival architectures. The focus of competition shifts from higher performance to lower cost and to differentiation via minor design variations and strategic positioning tactics (Porter, 1985). Social structures arise that reinforce this stable state; standard operating procedures are predicated on the reigning technical order, organizational power structures reflect dependencies that are partly governed by technology, and institutional networks with powerful norms arise whose shape is partly determined by an industry's technical regime (Schön, 1971; Hughes, 1987; Henderson and Clark, 1990). An era of incremental change persists until it is ended by another technological discontinuity (Abernathy, 1978; Landau, 1984; Tushman and Anderson, 1986).

A number of case studies have suggested that the cumulative effect of numerous incremental advances accounts for the majority of technical progress in industry (Myers and Marquis, 1969). Rosenberg (1976) contended that most of the progress attributable to major innovations actually stems from the series of minor improvements that follow them. More recently, practitioners (e.g., Imai, 1986; Gomory, 1989) have criticized the mentality that seeks large breakthroughs instead of a continuous series of small, step-by-step advances. However, the contention that most technical progress in an industry occurs during eras of incremental change has never been subjected to empirical test. The relative importance of improvements following a dominant design, as opposed to improvements leading up to a dominant design, has yet to be established.

The evolutionary model presented here suggests that variation is generated by technological discontinuities and subsequent eras of ferment. If an accelerated rate of variation speeds the pace of innovation, we might expect that less technical advance occurs during periods of incremental change than during eras of ferment. Contrary to the conventional view, we predict:

Hypothesis 8: Most of the total performance improvement over the lifetime of a technology will occur outside the era of incremental change.

The hypotheses were tested with longitudinal data from three industries, using the model of the technology cycle as a reference point.

METHOD

Industries Studied

Two of Tushman and Anderson's (1986) product classes—portland cement manufacture and minicomputer manufacture—were included in this study. In addition, three branches of glass manufacture were investigated: window glass, plate glass, and glass containers. As in the other two industries, archival data sources permitted a complete census of population members over time and the identification of performance changes in key technological parameters. Table 2 summarizes the measures and data sources used for all three product classes. Data gathered here stem from an exhaustive study of every industry directory and trade journal covering each industry, in addition to several useful historical works listed in the references.

Caution should be exercised in generalizing the results of this study, since so few industries were included. The industries studied here were not randomly selected and may not be representative of industries in general, particularly in nonmanufacturing sectors. They were chosen because data were available to track technological progress from the beginning of the industry's history. These industries were also chosen because none was dominated by a single firm, which would

Table 2

Summary of Variables, Measures, and Data Sources

Variable	Industry (time span)	Measure	Data source	Range
Technological progress	Cement (90 years)	% improvement in capacity of largest kiln.	*Rock Products, American Cement Directory,* Lesley (1924).	0–320%
	Glass containers (85 years)	% improvement in capacity of fastest machine.	Scoville (1948), Davis (1949), Emhart (1974), *Glass Industry.*	0–292%
	Flat glass (80 years)	% improvement in capacity of fastest machine.	Scoville (1948), Davis (1949), *Glass Industry.*	0–392%
	Minicomputers (24 years)	% improvement in CPU speed of fastest computer.	*Computers and Automation, Computerworld.*	0–4400%
Market share of competing designs (dominant design)	Cement	New kiln installations.	*Rock Products, American Cement Directory.*	0–48 new kilns
	Glass containers	New glass-container machines.	*Glass Industry,* Barnett (1926).	0–65 new machines
	Flat glass	New flat-glass machines.	*Glass Industry, National Glass Budget* directories.	0–23 new machines
	Minicomputers	Minicomputer sales by model.	International Data Corporation Processor Installation Census, *Computers and Automation.*	0–168,687 new units
Locus of innovation and standardization	Cement	Number of newcomers and incumbents among earliest to adopt a discontinuity or dominant design.	*Rock Products, American Cement Directory.*	See Table 4
	Glass containers		Barnett (1926), Scoville (1948), *National Glass Budget.*	
	Flat glass		Scoville (1948), *National Glass Budget.*	
	Minicomputers		International Data Corporation Processor Installation Census, *Computers and Automation.*	

make it difficult to disentangle technological and organizational evolution, and none was subject to significant regulation. However, there is no reason to suspect that the sample is biased in any particular way. These were the only industries studied; none were dropped because they did not fit the model.

In addition, it should be noted that findings concerning newcomers and industry incumbents (hypothesis 7) may be functions of industry age. The first cement discontinuity occurred when the industry had been in existence sixteen years; the first discontinuity in container glass and flat glass occurred when each respective industry had been in existence over a century. In contrast, the last minicomputer discontinuity occurred when the industry had been in existence fifteen years. Thus incumbents had considerably more time in the glass and cement industries to become established than was the case in the minicomputer industry.

Discontinuities and Dominant Designs

As in Tushman and Anderson's study, a key performance parameter was tracked over time. We followed Tushman and Anderson's practice of focusing on barrels-per-day production capacity for cement and CPU cycle time for minicomputers. Since glass containers and sheets are commodities, the key variable is machine production capacity, expressed in containers per minute or square feet per hour.

A technological discontinuity is identified when an innovation (a) pushes forward the performance frontier along the parameter of interest by a significant amount and (b) does so by changing the product or process design, as opposed to merely enlarging the scale of existing designs. We began by tracking the state of the art, using the parameters described above, for each year of the industry's existence, producing figures like 2a and 2b, above, which resemble Figures 1a and 1c in Tushman and Anderson (1986). For each advance in the frontier, we asked whether it was produced by a new architecture or a version of an existing architecture. Only those peaks in the figure that are associated with a new product or process design were counted as discontinuities; other peaks were typically attributable to elaborations of a previous discontinuity (e.g., adding arms to a glass machine or incrementally lengthening a cement kiln).

Empirically, a dominant design was defined as a single configuration or a narrow range of configurations that accounted for over 50 percent of new product sales or new process installations and maintained a 50-percent market share for at least four years. Archival sources, described in Table 2, were used to identify every new cement kiln installed after a discontinuity and every minicomputer sold after a discontinuity, permitting the specification of the year that a particular design achieved a 50-percent market share. The era of ferment depicted in Figure 1, above, was therefore defined as the period from the year a discontinuous innovation was first introduced to the year a single design first achieved a 50-percent market share, including endpoints. By examining peaks in the technological frontier, we were able to determine whether the dominant design embodied the state of the art at the time it achieved dominance.

Dominant Designs

Using the sources for the glass industry cited in Table 2, it was not possible to construct a complete census of glass machines, as was possible for cement kilns and minicomputers. Enough data were available to show all discontinuities in flat glass and all discontinuities in container glass through 1960. Additionally, data were fairly complete for periods immediately following a discontinuity, permitting identification of a dominant design and its first five adopters. However, it was not possible to construct a complete census of all glass machinery during each era of incremental change, and thus the glass industry was not used in testing hypothesis 1.

Competence Enhancement and Competence Destruction

For a contemporary innovation, one could measure competence enhancement and competence destruction by constructing an index, reflecting such factors as the amount of retraining required to master a new technology, the number of new skills a firm would have to acquire to exploit an innovation, or the degree to which models based on the old technology could be retrofitted with the new. One might also poll experts familiar with an industry's technology to see whether there is general agreement concerning the degree to which a new technology renders its predecessor obsolete.

Such data on technical competence were unavailable for these historical innovations. Firms themselves were unable to reconstruct how they adopted a new technology, and technical experts were not familiar with how their industries had evolved. Assessing how an innovation affected previous know-how must rest on the judgment and informed argument of the historian. The Appendix provides a brief description of every discontinuity and dominant design identified in Table 1, indicating why we classified each as competence-enhancing or competence-destroying. We believe the distinctions made in the 16 discontinuities are sufficiently clear-cut that future scholars studying the sources cited in Table 2 and in the references would reach similar conclusions.

Newcomers and Incumbents

In determining whether the pool of firms pioneering a discontinuity or dominant design consists of newcomers or incumbents, one must decide how many organizations to include in the group of trailblazers. The decision rule was to use the maximum number that could be identified reliably, given available data. For certain glass-industry innovations, only the first five firms to employ a particular type of machine could be distinguished. To weight each discontinuity equally, the first five firms were also used as the pool of early adopters for cement and minicomputer innovations and dominant designs. The choice of five pioneers is admittedly arbitrary but represents the most inclusive definition possible with existing archival sources. In all cases, only the year in which a firm introduced a particular design could be established; thus in many instances, it was impossible to specify which of several firms was the fifth pioneer. In such cases of ties, all firms that introduced the new technology or dominant design in the same year as the fifth pioneer were included in the pool of early adopters, resulting in a pool size greater than five.

A firm was considered to have entered an industry when it sold its first minicomputer, barrel of cement, sheet of glass, or container. For each technological cycle, a firm was classified as an incumbent with respect to a given discontinuity if it entered the industry before the discontinuity; otherwise, it was classified as a newcomer.

It must be noted that the statistical tests reported here are based on a limited number of cases from a small set of industries and that these historically linked observations are not truly independent. The purpose of employing statistical tests is to give the reader a guidepost indicating the degree to which the hypotheses are supported with the limited empirical data available. A far larger sample would be required to provide the statistical power necessary to eliminate conclusively a rival hypothesis.

RESULTS

Hypothesis 1 asserted that the mean number of new product or process models would be higher during the era of ferment than during the era of incremental change. As noted above, empirical testing of this hypothesis was limited to the cement and minicomputer industries. Table 1, above, shows that within minicomputers, there was no dominant design and hence no era of incremental change following the first discontinuity; following the second, the era of incremental change was only one year long. Therefore, hypothesis 1 could only be tested for the third discontinuity. Within cement, the first discontinuity also did not culminate in a dominant design, and for the second discontinuity, the era of incremental change was only two years long. The remaining discontinuities were suited to testing hypothesis 1.

Table 3 reports the mean number of new designs per year during eras of ferment and incremental change. In support of hypothesis 1, in three of four comparisons, the mean number of new designs per year was significantly greater during eras of ferment than during eras of incremental change. In minicomputers, there was an average of 23.67 models per year introduced during the era of ferment after semiconductor memory, vs. 16.40 models per year introduced during the following era of incremental change. In cement, the average number of new kilns was significantly greater during the eras

Table 3

New Designs within Technology Cycles: Ferment vs. Incremental Change

Industry	Discontinuity	Era	Years	Mean new designs per year	T	D.f.
Cement	Edison long kiln	Ferment	1903–1910	19.75		
		Incremental change	1911–1959	9.55	3.136•••	55
	Computerized kiln	Ferment	1960–1965	10.00		
		Incremental change	1966–1971	6.00	1.940••	10
	Suspension preheating	Ferment	1972–1979	5.75		
		Incremental change	1980–1985	3.67	1.138	11
Minicomputers	Semiconductor memory	Ferment	1971–1976	23.67		
		Incremental change	1977–1981	16.40	1.917•	9

• $p < .06$; ••$p < .05$; •••$p < .01$; one-tailed *t*-tests of differences between the means.

of ferment following the Edison kiln and process control than during the respective eras of incremental change. After suspension preheating, however, while there were more kilns introduced during the era of ferment than during the era of incremental change, this difference was not statistically significant. Consistent with hypothesis 1, then, eras of ferment were associated with more product or process variability than subsequent eras of incremental change.

Hypothesis 2a suggested that the era of ferment would be longer following competence-destroying discontinuities than following competence-enhancing discontinuities. Column 6 of Table 1, above, shows the length of each era of ferment (time to standard), while column 3 shows whether each discontinuity was classified as competence-enhancing or competence-destroying (see the Appendix for more detail). In support of hypothesis 2a, the length of the era of ferment averages 11.16 years for competence-destroying discontinuities, versus 8.0 years for competence-enhancing discontinuities ($t = 1.72$, d.f. $= 10$; $p < .06$, one-tailed test). As predicted, the period of heightened variation after competence-destroying discontinuities is significantly longer than the period of variation after competence-enhancing discontinuities.

Hypothesis 2b argued that when successive competence-enhancing discontinuities occur, the length of the era of ferment would grow shorter with each cycle, since the same fundamental competences are being reinforced. Successive competence-enhancing discontinuities are rare; only twice in the populations studied do two competence-enhancing discontinuities occur in sequence. In both cases—process control of cement kilns and double-gobbing glass container machinery—the second era of ferment was shorter than the first. While no firm conclusions can be drawn from two cases, the evidence is consistent with the idea that industries institutionalize their basic competences. There is no general trend for the second of two successive cycles to have a shorter era of ferment than its predecessor, however. There are eight cases of successive discontinuities that were followed by dominant designs. In four of these cases, the second cycle had a shorter duration than the first, while in four others, the first cycle had the same or shorter duration than the second.

Hypothesis 3 argued that in regimes of low appropriability, a single dominant design would emerge after each discontinuity. Of the 16 discontinuities identified in Table 1, above, two (continuous forming and float glass) were cases in which technological competition was constrained by patent protection. In these two high-appropriability cases, no dominant design emerged. Fourteen discontinuities remain as the sample to test hypothesis 3.

Column 4 of Table 1 indicated that a single design garnered a 50-percent share of new product sales or process installations in 12 of these 14 cases; in two instances, no dominant design emerged. Hypothesis 3 is supported at the 95-percent confidence level ($p = .006$).[2] A single dominant design generally emerges to capture and maintain a greater share of the market than all rivals put together.

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[2] We assume that each observed discontinuity represents an independent draw from the population of all technological discontinuities. If hypothesis 3 had no predictive power at all, then the probability of the result being in the predicted direction on any given trial would be .5. The probability that at least 12 of 14 cases would be in the predicted direction is given by the binomial distribution using a one-tailed test (Blalock, 1979: 169–170). In this case,

$$\sum_{r-12}^{14} \binom{14}{r} \cdot 5^{r} \cdot 5^{(14-r)}$$

sums to a probability of .006.

Examination of the two low-appropriability cases, in which dominant designs were not observed, provides insight on conditions under which dominant designs might not emerge. In both cases (the continuous vertical cement kiln and the transistorized minicomputer), the industries were in their infancy, and the initial breakthrough technologies were quickly (within four years) superseded by revolutionary advances. It may be when there are relatively few competitors (there were fewer than 10 cement firms in 1888 and fewer than 5 minicomputer firms in 1960) and when technological discontinuities follow each other within a few years, that selection processes do not have time to operate before the next era of ferment is initiated.

Dominant designs emerge as industry standards that, in turn, shape further technological evolution within a product class. If, however, a dominant design emerges after sales peak in a product class, the concept of dominant design loses its significance. Hypothesis 4 argued that dominant designs would spark increased demand and that product-class sales would peak after their emergence. Column 7 in Table 1, above, showed the year in which sales of the new technology peaked (in constant dollars for minicomputers; in new machine installations for cement and glass) following each technological discontinuity. In each of the 12 cases in which a dominant design emerges, sales peak after the dominant design ($p = .0002$, one-tailed binomial probability). In no case did sales peak in the era of ferment or remain stable after the dominant design emerged. As predicted in hypotheses 3 and 4, dominant designs do emerge after technological discontinuities and, in turn, stimulate subsequent industry demand.

Hypothesis 5 stated that a discontinuous innovation would not itself become a dominant design. Comparing columns 1 and 4 of Table 1, of the 12 discontinuities that resulted in a dominant design, none of the discontinuities ever emerged as the industry standard ($p = .0002$, one-tailed binomial probability). When one design came to account for 50 percent or more of the market, it was always an evolution of the original breakthrough. In support of hypothesis 5, a discontinuous innovation never itself set an industry standard; some subsequent improvement became the benchmark.

Hypothesis 6 stated that a dominant design would not be located on the frontier of technical performance at the time it became dominant. Columns 8 and 9 of Table 1 provide support for this hypothesis. Column 8 showed the performance of the dominant design (measured in barrels per day, containers per minute, square feet per hour, or CPU speed), while column 9 showed the maximum value of that measure achieved in the year the design achieved dominance. When the value for the frontier in column 9 is greater than the value for the dominant design in column 8, then at least one rival design is superior to the industry standard in terms of the criterion measured here. In only 2 of 12 cases (the improved Lubbers machine and the 500–580-foot process-controlled kiln) were dominant designs the highest-capacity cement kiln, the fastest glass-producing machine, or the speediest minicomputer in the industry by the time they achieved a 50-percent market share. Designs that emerged as standards from an era of design competition were technically conservative when introduced. In 10 of 12 cases they lagged behind achievable limits of the technology by the time their dominance was established ($p = .017$, one-tailed binomial probability).

Hypothesis 7 argued that industry incumbents would pioneer dominant designs based on competence-enhancing breakthroughs, while newcomers would pioneer dominant designs based on competence-destroying breakthroughs. Table 4 shows, for each dominant design, how many newcomers and incumbents were among the pool of early adopters. Hypothesis 7 is supported for competence-enhancing discontinuities. Incumbents outnumber newcomers by more than a 3-to-1 ratio ($t = 2.30$, $p < .05$). Hypothesis 7, however, is not supported for competence-destroying discontinuities. While the mean number of newcomers is greater than the mean number of incumbents, this difference is not statistically significant ($t = .86$). In 2 of 5 cases, incumbents predominated in the pool of early adopters. Where Tushman and Anderson (1986) found that newcomers pioneer competence-destroying innovations, these results indicate that the dominant designs that follow these breakthroughs are initiated by a mixture of newcomers and incumbents. The process of setting industry standards may require a combination of new thinking and institutional experience. Perhaps new entrants are required to initiate the creative destruction that makes an entrenched technical regime obsolete, but established firms contribute to the creation of technical order from the intense ferment triggered by competence-destroying technical change.

Table 4

Pioneers of Dominant Designs

Industry	Discontinuity	Dominant design	Dominant design pioneers Incumbents	Dominant design pioneers New Entrants
		Competence-enhancing discontinuities		
Cement	Continuous vertical kiln	None	–	–
	Edison long rotary kiln	120–125 ft. kiln	6	4
	Computerized long kiln	500–580 ft. kiln	4	1
Containers	Gob-fed machinery	IS Model C	3	0
	Double gobbing	5-section Model E	–	–
Window	Machine cylinder	Improved Lubbers	1	0
Minicomputers	Semiconductor memory	16-bit machine, 16K MOS memory	5	1
Mean number of pioneers of each type			3.80	1.20
One-tailed difference of means test: $t = 2.298$ ($p < .05$); d.f. = 8				
		Competence-destroying discontinuities		
Cement	Rotary kiln	6 × 60 ft. Hurry-Seaman	1	9
	Suspension preheating	4-stage cyclone with flash calciner	4	1
Containers	Semiautomatic machinery	United Machine	–	–
Containers	Owens machine	AN/AR series	3	4
Window	Drawing machines	Fourcault machine	4	1
Plate	Continuous forming	None	–	–
Flat	Float glass	None	–	–
Minicomputers	Solid-state circuits	None	–	–
	Integrated circuits	16-bit machine, core memory	1	5
Mean number of pioneers of each type			2.60	4.00
One-tailed difference of means test: $t = .858$; d.f. = 8				

Hypothesis 8 stated that more technical progress results from the discontinuity and era of ferment than from accumulating incremental advance. Table 5 shows, for each of 11 discontinuities, where data were available, the proportion of total advance within each cycle attributable to the discontinuity, advances during the era of ferment, and advances during the era of incremental change. Only in the case of the computerized cement kiln does the accumulation of small improvements during the era of incremental change account for more than 50 percent of the total advance during the cycle. In the float-glass case, improvements following the original discontinuity accounted for 72 percent of total progress, but this includes all advances following the discontinuity, since no dominant design arose. In 7 of the 11 cases, the discontinuity alone accounted for more than half the total progress within the cycle. In the remaining two cases, the discontinuity and era of ferment together accounted for the majority of technical advance. On average, 19.5 percent of all progress within a technological cycle cumulates during the era of incremental change, significantly less than those technical advances that occur with the discontinuity itself and during the era of ferment.

We can demonstrate this by presuming that the eleven innovations shown in Table 5 represent a sample from the universe of technology cycles and, across all technology cycles, eras of incremental change account for 50 percent of all technological progress. Our null hypothesis is that $p_u = .5$, where p_u is the proportion of advance due to incremental change in the population of all technology cycles. In this sample of 11 cycles, p_s (the proportion of advance to incremental change in the sample) is on average .1955: assigning

Table 5

Technical Advance Due to Discontinuities, Eras of Ferment, and Eras of Incremental Change*

	Percentage of total technological progress in each cycle					
	Due to discontinuity		During era of ferment		During era of incremental change	
Discontinuity	Progress	%	Progress	%	Progress	%
Cement kiln capacity (barrels per day)						
Rotary kiln	80 to 160	76	160 to 185	24	None	0
Edison long rotary kiln	185 to 800	14	800 to 2,500	40	2,500 to 4,500	46
Computerized kiln	4,500 to 10,000	36	10,000 to 12,000	13	12,000 to 20,000	51
Container machine capacity (bottles per minute)						
Semiautomatic machine	1.66 to 3.18	100	None	0	None	0
Owens machine	3.18 to 12.5	16	12.5 to 40	46	40 to 62.5	38
Window glass machine capacity (square feet per hour)						
Lubbers machine	150 to 500	64	500 to 700	36	None	0
Colburn machine	700 to 1,160	100	None	0	None	0
Float glass	1,160 to 5,707	28	5,707 to 17,600	72	[No dominant design]	
Minicomputer CPU cycle time (microseconds)						
Solid-state circuits	540 to 12	99	12 to 6	1	[No dominant design]	
Integrated circuits	6 to 1.6	84	1.6 to .775	16	None	0
Semiconductor memory	.775 to .3	82	.3 to .24	11	.24 to .2	7
Average % advance in each era (column total/number of eras observed):		63.55		16.90		19.55

* To be conservative, all progress following the float-glass and solid-state discontinuities was assigned to the era of incremental change, though no dominant design emerged to end the era of ferment.

all the progress in float glass and solid-state circuits in Table 5 to the era of incremental change, on average 19.55 percent of all progress occurs during the era of incremental change. By a simple binomial test of proportions (Blalock, 1979: 199),

$$Z = \frac{p_s - p_u}{p_u(1 - p_u)/N} = -2.02.$$

We would expect a Z value as small as -2.02 in fewer than 5 out of 100 samples. At the .05 level of confidence, we can reject the hypothesis that incremental change accounts for a majority of technical advance. Hypothesis 8 is thus supported.

DISCUSSION AND CONCLUSIONS

Limitations

We caution against overgeneralizing the results of this research. Sixteen discontinuities were observed; such a small number limits one's ability to discriminate with statistical power. Similarly, the three industries studied are not representative of all manufacturing industries, much less service sectors. This research has employed simple tests to see whether contrasts between the time periods the theory defines occur in the anticipated direction. The general empirical support obtained for the hypotheses indicates that the technology-cycle model helps explain some nonobvious predictions whose falsification would have cast serious doubt on the underlying theory. An adequate test of this theory would require more complex modelling and, in turn, many more observations. Nonetheless, the industries studied are diverse, the time span is long, and the quality of the data is exceptional, given the difficulties of collecting historical information.

Another limitation is that only one key performance dimension per industry was studied, and performance is a multidimensional construct. In addition, we know that some innovations that are measurably superior to existing technology never do achieve market success; this study does not tell us what distinguishes the breakthrough innovations from those might-have-been technical revolutions. The concept of competence enhancement and destruction would benefit greatly from in-depth investigation and refinement. Researchers may find it difficult to predict in advance whether an innovation will build on existing know-how or make it obsolete. Additionally, a complex bundle of competences characterizes economic organizations, only some of which are affected by most innovations; future studies might address the role of firm-level complementary assets (Teece, 1986) in addition to industry-level core technical know-how.

Dominant Designs

Dominant designs are critical junctures in the evolution of technology. Because no technology dominates all dimensions of merit, we argued that the closing on an industry standard is an inherently political and organizational phenomenon constrained by technical possibilities. The passage of an industry from ferment to order is not an engineering issue as much as a sociological one. Since stakes are substantial, a complicated array of organizational and collective forces bear on the emergence of a single standard. Actions by firms alone and in conjunction with strategic alliances attempt to shape standards (e.g., Landes, 1969; Hughes, 1983). Further, institutional forces such as industry associations and regulatory agencies affect these standards, as well as concerted efforts by suppliers, vendors, and customers (David, 1987; Farrell and Saloner, 1985). The establishment of a particular technical regime may have national repercussions, leading to the direct involvement of sovereign states in the process of technological evolution (Rosenberg, 1982; Nelson, 1984). Future research could explore the social dynamics of industry standardization. Because these issues rest at the confluence of economics, sociology, history, and organization theory, this is an area in which interdisciplinary synthesis is likely to be particularly fruitful.

Further studies should also more richly characterize the organizations that pioneer standards. This research focused on whether the pioneer was an incumbent or a newcomer; a host of other organizational features and characteristics of the innovation may influence pioneering behavior. One might ask whether the pioneers were industry leaders or smaller incumbents; whether they were larger or smaller than the average incumbent; whether they were centrally located in the industry's institutional network; and whether political assets contributed to their ability to foster standards.

Under what conditions do dominant designs not emerge? Of the 16 discontinuities studied, four did not lead to dominant designs. Because dominant designs emerge out of demand-driven competition between alternative technological orders, if either demand is low or technological competition is stunted or cut short, no industry standards will emerge for a given technological breakthrough. While not investigated here, dominant designs might also not evolve in product classes with either limited demand or demand for custom-made products (Houndshell, 1984). Future research could more carefully explore the conditions under which industry standards do not emerge.

The technology-cycle concept suggests that the competitive environment changes in repeated patterns over time. The pace of variation and selection among designs ebbs and flows, turning on discontinuities and dominant designs. These recurring technological events are linked to systematic environmental change (Tushman and Anderson, 1986) and population dynamics (Barnett, 1990). Technological discontinuities and dominant designs might also influence entry and exit rates within populations as well as change the balance between first-movers and efficient producers (e.g., Brittain and Freeman, 1980).

Technological cycles might also influence organizational evolution (Tushman and Romanelli, 1985; Henderson and Clark, 1990). As technology evolves, organizations are faced again and again with a set of recurring challenges: pioneering or being threatened by substitute technology; adopting some version of a breakthrough innovation in the face of extraordinary rates of variation; recognizing, shaping, or adopting an emerging standard; surviving in an environment in which technology advances incrementally and competitive advantage depends on continuous improvement instead of novelty.

Dominant designs and technological discontinuities pose crucial competitive challenges and strategic choices for organizations.

The model of technological evolution explored here thus has several organizational consequences. Organizations must develop diverse competences both to shape and deal with technological evolution. While technological breakthroughs may be unpredictable events, firms must develop the capacity either to initiate these discontinuities or respond rapidly (e.g., Cohen and Levinthal, 1990). Because industry standards are not known in advance and are influenced by interorganizational dynamics, organizations must be able to combine technological capabilities with the ability to shape interorganizational networks and coalitions to influence the development of industry standards. The consequences of either ignoring technological discontinuities or of losing the battle for industry standards are substantial (Noble, 1984; Foster, 1986; David and Bunn, 1988). Finally, during the period of incremental change, organizations need to develop the ability to produce incremental innovation even as they develop competencies to develop subsequent technological breakthroughs. This approach to technological evolution puts a premium on the firm's ability to develop multiple, often inconsistent competencies simultaneously (Burgelman, 1983). Because technology is partly a socially driven phenomenon, organizations may need to develop heterogeneous organizational and interorganizational competencies to deal with the divergent technological, organizational, and interorganizational requirements as technology cycles unfold in the course of their daily activities. The challenge is for organizations to survive and thrive through the complex dynamics that characterize technological change.

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APPENDIX: Classification of Competence-enhancing and Competence-destroying Discontinuities

Table 1 describes the sixteen technological discontinuities observed in this study and classifies each as competence-enhancing or competence-destroying. This section briefly describes each case. Key data sources are described in Table 2 and are listed in the references.

Cement

The earliest American cement was made in vertical kilns via a batch process. In 1888, the first *continuous vertical kilns* were imported from Germany. These imitated the older kilns but eliminated the need for laborers to feed the kiln with a shovel. This innovation was *competence-enhancing* because it operated exactly as older vertical kilns did, but faster and with less labor.

In 1982, the first *rotary kiln* appeared in the United States. Here the cement spirals down an inclined tube, heating gradually on its journey. Rotary kilns are radically different from vertical kilns and forced producers to re-learn the art of cement manufacture. The way in which raw materials were transformed into "clinker" depended on a host of new factors, including the rotation rate, incline, type of kiln lining, amount, and placement of heat along the tube, etc. Rotary kilns were *competence-destroying.*

The accepted wisdom at the turn of the century was that a rotary kiln could not exceed 60 feet in length, or it would warp and crack. Thomas Edison broke through the barrier with a new, reinforced rotary kiln 150 feet in length, dramatically increasing the capacity of the rotary kiln. Adapting to *Edison kilns* required new capital expenditures, but the process understanding that cement manufacturers had developed through experience with rotary kilns was still valid. Edison kilns were *competence-enhancing,* representing a new design that extended the reach of existing know-how.

The length of the kiln, and hence its capacity, appeared to have reached a physical limit by 1960. Kilns had gotten so large that adjustments made by an operator (e.g., in speed of rotation) could take hours to have the desired effect. The introduction of *process control* computers in 1960 eliminated this constraint. The computer could continuously monitor the kiln via sensors and make fine adjustments. Kiln capacity was no longer constrained by human limitations, and kilns grew dramatically in size and capacity in the early 1960s, culminating in the mammoth Dundee kiln. The substitution of computers for human operators allowed cement makers to control a very well-understood process more closely than ever before, building on decades of experience with rotary kilns; this is a *competence-enhancing* innovation.

The oil embargo of 1973 fell heavily on the cement industry, one of the most energy-intensive sectors of the economy. The industry returned to energy-efficient vertical kilns developed in Europe, which employed *suspension preheating.* Most of the clinkering took place in a chamber, where fine particles of raw material were whirled in hot air. This clinkering process is fundamentally different from the gradual heating of a mass of raw material in a ceramic-lined tube; it builds on an entirely different body of know-how pioneered in Europe and Japan. Rotary kiln know-how contributed little to understanding the new process; the return to vertical kiln technology was *competence-destroying.*

Glass Containers

Originally, flasks and bottles were blown by hand, and the artisans who made glass containers were among the most highly skilled craftsmen of the nineteenth century. In 1893, the first semiautomatic machine for making bottles was introduced. It formed bottles by a process of pressing rather than blowing and allowed a semiskilled operator to outpace the production of the most skilled hand blower. This innovation was *competence-destroying;* employing the best artisans was no longer the key to container manufacture.

The *Owens machine* produced its first bottle in 1903. This device employed a vacuum to suck glass into a mold, whence it was formed into a bottle, employing a completely different mechanical principle than the semiautomatic machines. It also dispensed with the skills needed to operate a semiautomatic machine, since it was fully automatic. As a result, it was *competence-destroying,* overturning know-how relevant both to semiautomatic production and to the remaining craftsmen.

The Owens machine had an inherent physical limitation: it operated by moving the bottle mold to the source of molten glass. The machine weighed many tons, and its speed was accordingly limited by sheer inertia. A scientist named Karl Peiler devised the *gob feeder,* a method for moving the glass to the mold. The gob feeder was *competence-enhancing* from the perspective of the vast majority of glass container manufacturers who were unable to license the Owens patents and still employed the semiautomatic process. The gob feeder could be retrofitted to most semiautomatic machines, rendering them fully automatic. The experience and know-how gained with semiautomatic machines was transferrable to the new generation of equipment.

In 1937, a seemingly simple development again changed the industry: the advent of *double gobbing.* Learning how to make a gob feeder serve two molds at once took many more years of research at Hartford Empire, and the breakthrough revolutionized gob-feeding technology. However, the new technology built on the base of knowledge about gob formation that had been built up over the years, and many single-gob machines were retrofitted with the new devices, greatly extending their productivity. Double gobbing was a *competence-enhancing* innovation.

Flat Glass

See text for a description of technology evolution in window and plate glass.

Minicomputers

The first minicomputer was introduced by Burroughs in 1956. Like all computers of that era, it employed vacuum tubes. The Packard-Bell 250, which came on the market in 1960, was the first minicomputer to employ *solid-state circuits,* dramatically increasing speed. Knowledge about vacuum tubes does not carry over into solid-state transistors; the solid-state engineer had to master a new body of knowledge based on semiconduction. The transistor revolution was *competence-destroying.*

Dominant Designs

The replacement of transistors with *integrated circuits,* pioneered for minicomputers in 1965 with the DEC PDP-8, was *competence-destroying.* The computer engineer now had to be able to design logic circuitry etched onto a chip, rather than hook discrete components together with wires. The designer could not simply buy chips off the shelf; the architecture of the computer itself was expressed in silicon, not in the wiring together of discrete components. Knowing how to wire transistors together is different from being able to design an integrated circuit.

By the late 1960s, doughnut-shaped "magnetic cores" were the memory standard for minicomputers. In 1971, Data General introduced the first minicomputer with *semiconductor memory.* However, the impact of semiconductor technology was *competence-enhancing.* Minicomputer engineers did not have to design memory chips themselves; they merely purchased the chips from semiconductor manufacturers. Unlike logic circuitry, which differed from computer to computer, memory circuitry was standard; the computer engineer simply had to design the system for putting data into memory or taking it out. The memory itself was a black-box from the minicomputer designer's point of view, as demonstrated by the fact that many existing minicomputers were retrofitted with semiconductor memory, no basic design changes being required.