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This paper focuses on patterns of technological change and on the impact of technological breakthroughs on environmental conditions. Using data from the minicomputer, cement, and airline industries from their births through 1980, we demonstrate that technology evolves through periods of incremental change punctuated by technological breakthroughs that either enhance or destroy the competence of firms in an industry. These breakthroughs, or technological discontinuities, significantly increase both environmental uncertainty and munificence. The study shows that while competence-destroying discontinuities are initiated by new firms and are associated with increased environmental turbulence, competence-enhancing discontinuities are initiated by existing firms and are associated with decreased environmental turbulence. These effects decrease over successive discontinuities. Those firms that initiate major technological changes grow more rapidly than other firms.•

Since Barnard's (1938) and Selznick's (1949) seminal work, one of the richest streams of research in organizational theory has centered on organization-environment relations (see Starbuck, 1983, for a review). Recent work on organizational life cycles (Miller and Friesen, 1984; Tushman and Romanelli, 1985), organizational adaptation (Aldrich and Auster, 1986), population dynamics (Freeman, 1982), executive succession (Carroll, 1984), and strategy (e.g., Harrigan, 1983) hinges on environment-organization linkages. Environments pose constraints and opportunities for organizational action (Hrebiniak and Joyce, 1985).

If organizational outcomes are critically influenced by the context within which they occur, then better understanding of organizational dynamics requires that we more fully understand determinants of environmental change. While there has been substantial research on environmental conditions and organizational relations (see review in Downey and Ireland, 1979), relatively little research has examined how competitive environments change over time. While it is agreed that environmental conditions are shaped by competitive, legal, political, and technological factors (e.g., Starbuck, 1983; Romanelli and Tushman, 1986), and the interplay between them (Horwitch, 1982; Noble, 1984), there is little data on how these factors change over time or how they affect environmental conditions.

This paper focuses on technology as a central force in shaping environmental conditions. As technological factors shape appropriate organizational forms (McKelvey, 1982), fundamental technological change affects the rise and fall of populations within organizational communities (Astley, 1985). Basic technological innovation affects not only a given population, but also those populations within technologically interdependent communities. For example, major changes in semiconductor technology affected semiconductor firms as well as computer and automotive firms. Technology is, then, an important source of environmental variation and hence a critical factor affecting population dynamics.

This paper specifically investigates patterns of technological change and their impact on environmental conditions. Building on a considerable body of research on technological change, we argue and empirically demonstrate that patterned changes

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in technology dramatically affect environmental conditions. There exist measurable patterns of technological change that generate consistent patterns of environmental change over time across three diverse industries. While technology is but one force driving the course of environmental evolution, it is a key building block to better understand how environments and ultimately organizations evolve over time.

TECHNOLOGY AND TECHNOLOGICAL DISCONTINUITIES

Technology can be defined as those tools, devices, and knowledge that mediate between inputs and outputs (process technology) and/or that create new products or services (product technology) (Rosenberg, 1972). Technological change has an unequivocal impact on economic growth (Solow, 1957; Klein, 1984) and on the development of industries (Lawrence and Dyer, 1983). The impact of technology and technological change on environmental conditions is, however, less clear.

For over thirty years, technology and workflows have been central topics in organizational theory (e.g., Gerwin, 1981). Most studies of technology in organizational theory, however, have been either cross sectional in design (e.g., Woodward, 1965), have taken place in technologically stable settings (e.g., public and not-for-profit settings), or simply have treated technology as a constant (Astley, 1985). Since technology has been taken as a given, there has been a conspicuous lack of clarity concerning how and why technologies change and how technological change affects environmental and/or organizational evolution. An exception is the work of Brittain and Freeman (1980).

There is a substantial literature on technological evolution and change (e.g., Mensch, 1979; Sahal, 1981; Dutton and Thomas, 1985). Some suggest that technological change is inherently a chance or spontaneous event driven by technological genius, as did Taton (1958) in his discussion of penicillin and radioactivity, and Schumpeter (1961). Others, like Gilfillan (1935), who described the multiple independent discoveries of sail for ships, suggest that technological change is a function of historical necessity; still others view technological progress as a function of economic demand and growth (Schmookler, 1966; Merton, 1968). An analysis of many different technologies over years of evolution strongly indicates that none of these perspectives alone captures the complexity of technological change. Technology seems to evolve in response to the interplay of history, individuals, and market demand. Technological change is a function of both variety and chance as well as structure and patterns (Morison, 1966; Sahal, 1981).

Case studies across a range of industries indicate that technological progress constitutes an evolutionary system punctuated by discontinuous change. Major product breakthroughs (e.g., jets or xerography) or process technological breakthroughs (e.g., float glass) are relatively rare and tend to be driven by individual genius (e.g., C. Carlson and xerography; A. Pilkington and float glass). These relatively rare discontinuities trigger a period of technological ferment. As a new product class opens (or following substitution of one product or process for a previous one), the rate of product variation is substantial as alternative product forms compete for dominance. An example is the competition between electric, wood, and internal combustion engines in automobiles or the competition between incompatible videocassette or microcomputer technologies. This technological experimentation and competition persists within a product class until a dominant design emerges as a synthesis of a number of proven concepts (Utterback and Abernathy, 1975; Abernathy, 1978).

A dominant design reflects the emergence of product-class standards and ends the period of technological ferment. Alternative designs are largely crowded out of the product class, and technological development focuses on elaborating a widely accepted product or process; the dominant design becomes a guidepost for further product or process change (Sahal, 1981; Abernathy and Clark, 1985). Dominant designs and associated shifts in product or process change have been found across industries. The Model T, the DC-3, the Fordson tractor, the Smith Model 5 typewriter and the PDP-11 minicomputer were dominant designs that dramatically shaped the evolution of their respective product classes.

Once a dominant design emerges, technological progress is driven by numerous incremental, improvement innovations (Myers and Marquis, 1969; Dutton and Thomas, 1985). For example, while the basic technology underlying xerography has not changed since Carlson's Model 914, the cumulative effect of numerous incremental changes on this dominant design has dramatically improved the speed, quality, and cost per unit of reprographic products (Dessauer, 1975). A similar effect was documented by Yin and Dutton (1986), who described the enormous performance benefits of incremental process improvement in oil refining.

Incremental technological progress, unlike the initial breakthrough, occurs through the interaction of many organizations stimulated by the prospect of economic returns. This is evident in Hollander's (1965) discussion of rayon, Tilton's (1971) study of semiconductors, and Rosenbloom and Abernathy's (1982) study of VCR technology. These incremental technological improvements enhance and extend the underlying technology and thus reinforce an established technical order.

Technological change is a bit-by-bit, cumulative process until it is punctuated by a major advance. Such discontinuities offer sharp price-performance improvements over existing technologies. Major technological innovations represent technical advance so significant that no increase in scale, efficiency, or design can make older technologies competitive with the new technology (Mensch, 1979; Sahal, 1981). Product discontinuities are reflected in the emergence of new product classes (e.g., airlines, automobiles, plain-paper copiers), in product substitution (e.g., transistors vs. vacuum tubes; diesel vs. steam locomotives), or in fundamental product improvements (e.g., jets vs. turbojets; LSI vs. VSLI semiconductor technology). Process discontinuities are reflected either in process substitution (e.g., mechanical ice making vs. natural ice harvesting; thermal vs. catalytic cracking in crude oil refining; artificial vs. natural gems) or in process innovations that result in radical improvements in industry-specific dimensions of merit (e.g., Dundee kiln in cement; Lubbers machinery in glass).

These major technological shifts can be classified as *competence-destroying* or *competence-enhancing* (see also Abernathy and Clark, 1985), because they either destroy or enhance the competence of existing firms in an industry. The former require new skills, abilities, and knowledge in both the development and production of the product. The hallmark of competence-destroying discontinuities is that mastery of the new technology fundamentally alters the set of relevant competences within a product class. For example, the knowledge and skills required to make glass using the float-glass method are quite different from those required to master other glass-making technologies. Diesel locomotives required new skills and knowledge that steam-engine manufacturers did not typically possess. Similarly, automatically controlled machine tools required wholesale changes in engineering, mechanical, and data-processing skills. These new technical and engineering requirements were well beyond and qualitatively different from those skills necessary to manufacture conventional paper-punched machine tools (Noble, 1984).

A competence-destroying product discontinuity either creates a new product class (e.g., xerography or automobiles) or substitutes for an existing product (e.g., diesel vs. steam locomotive; transistors vs. vacuum tubes). Competence-destroying process discontinuities represent a new way of making a given product. For example, the float-glass process in glass manufacture substituted for continuous grinding and polishing; mechanical ice making substituted for natural ice harvesting; planar processes substituted for the single-wafer process in semiconductors. In each case, the product remained essentially unchanged while the process by which it was made was fundamentally altered. Competence-destroying process breakthroughs may involve combining previously discrete steps into a more continuous flow (e.g., float glass) or may involve a completely different process (e.g., man-made gems).

Competence-destroying discontinuities are so fundamentally different from previously dominant technologies that the skills and knowledge base required to operate the core technology shift. Such major changes in skills, distinctive competence, and production processes are associated with major changes in the distribution of power and control within firms and industries (Chandler, 1977; Barley, 1986). For example, the ascendance of automatically controlled machine tooling increased the power of industrial engineers within the machine-tool industry (Noble, 1984), while the diffusion of high-volume production processes led to the rise of professional managers within more formally structured organizations (Chandler, 1977).

Competence-enhancing discontinuities are order-of-magnitude improvements in price/performance that build on existing know-how within a product class. Such innovations substitute for older technologies, yet do not render obsolete skills required to master the old technologies. Competence-enhancing product discontinuities represent an order-of-magnitude improvement over prior products yet build on existing know-how. For example, IBM's 360 series was a major improvement in price, performance, and features over prior models yet was developed through the synthesis of familiar technologies (Pugh, 1984). Similarly, the introduction of fan jets or of the screw propeller dramatically improved the speed of jets and ocean-going steamships, and aircraft producers and boatyards were able to take advantage of existing knowledge and skills and rapidly absorb these complementary technologies (Davies, 1972; Headrick, 1981).

Competence-enhancing process discontinuities are process innovations that result in an order-of-magnitude increase in the efficiency of producing a given product. For example, the Edison kiln was a major process innovation in cement manufacture that permitted enormous increases in production capacity yet built on existing skills in the cement industry (Lesley, 1924). Similarly, major process advances in semiconductor integration, strip steel, and glass production eliminated barriers to future growth in their product classes. These advances built on existing knowledge and skills and provided the core for subsequent incremental improvements (Dutton and Thomas, 1985).

Table 1 gives a typology of technological changes with examples of competence-destroying and competence-enhancing product and process technologies.

Table 1

A Typology of Product and Process Technological Changes

Technological Changes	
Competence-Destroying	Competence-Enhancing
Product	
New Product Class: Airlines (1924) Cement (1872) Plain-paper copying (1959)	*Major Product Improvements:* Jet → turbofan LSI → VSLI semiconductors Mechanical → electric typewriters Continuous aim cannons Nonreturnable → returnable bottles Thin-walled iron cylinder block engine
Product Substitution: Vacuum tubes → transistors Steam → diesel locomotives Piston → jet engines Records → compact disks Punched paper → automatic control machine tooling Discrete → integrated circuits Open → closed steel auto bodies	*Incremental Product Changes* *Dominant Designs:** PDP-11, VHS technology IBM 360, DC-3 Numerical control machine tools
Process	
Process Substitution: Natural → mechanical ice Natural → industrial gems Open hearth → basic oxygen furnace Individual wafer → planar process Continuous grinding → float glass Thermal cracking → catalytic cracking Vertical → rotary kiln Blown → drawn window glass	*Major Process Improvements:* Edison kiln Resistive metal deposition (semiconductors) Gob feeder (glass containers) Catalytic cracking → catalytic reforming *Incremental Process Improvements:* Learning by doing; numerous process improvements

*Some dominant designs are incremental improvements (e.g., PDP-11), while others are major improvements (e.g., DC-3, IBM 360).

Both technological discontinuities and dominant designs are only known in retrospect — technological superiority is no guarantee of success. The dominance of a substitute product (e.g., Wankel engines, supersonic jets, or bubble memory), substitute process (e.g., continuous casting), or a dominant design (e.g., VHS vs. beta videocasette systems) is a function of technological, market, legal, and social factors that cannot be fully known in advance. For example, the choice by vacuum tube makers such as RCA, GE, and Philco to concentrate on a dominant design for electron tubes in the early transistor days turned out, in retrospect, to have been an error (Tilton, 1971). Similarly, choices of standard record speeds, widths of railroad track, automatically controlled machine tool technologies or automated office equipment standards are often less a function of technical merit than of market or political power (Noble, 1984).

A number of product-class case studies indicate that technology progresses in stages through relatively long periods of incremental, competence-enhancing change elaborating a particular dominant design. These periods of increasing consolidation and learning-by-doing may be punctuated by competence-destroying technological discontinuities (i.e., product or process substitution) or by further competence-enhancing technological advance (e.g., revitalizing a given product or process with complementary technologies). Technological discontinuities trigger a period of technological ferment culminating in a dominant design and, in turn, leading to the next period of incremental, competence-enhancing, technological change. Thus, we hypothesize:

Hypothesis 1: Technological change within a product class will be characterized by long periods of incremental change punctuated by discontinuities.

Hypothesis 1a: Technological discontinuities are either competence enhancing (build on existing skills and know-how) or competence destroying (require fundamentally new skills and competences).

Competence-destroying and competence-enhancing discontinuities dramatically alter previously attainable price/performance relationships within a product class. Both create technological uncertainty as firms struggle to master an untested and incompletely understood product or process. Existing firms within an industry are in the best position to initiate and exploit new possibilities opened up by a discontinuity if it builds on competence they already possess. Competence-enhancing discontinuities tend to consolidate industry leadership; the rich are likely to get richer.

Competence-destroying discontinuities, in contrast, disrupt industry structure (Mensch, 1979). Skills that brought product-class leaders to preeminence are rendered largely obsolete; new firms founded to exploit the new technology will gain market share at the expense of organizations that, bound by traditions, sunk costs, and internal political constraints, remain committed to outmoded technology (Tilton, 1971; Hannan and Freeman, 1977). We thus hypothesize:

Hypothesis 2: The locus of innovation will differ for competence-destroying and competence-enhancing technological changes. Competence-destroying discontinuities will be initiated by new entrants, while competence-enhancing discontinuities will be initiated by existing firms.

TECHNOLOGICAL DISCONTINUITIES AND ORGANIZATIONAL ENVIRONMENTS

To determine the extent to which technological discontinuities affect environmental conditions, we build on Dess and Beard's (1984) review of environmental dimensions and examine two critical characteristics of organizational environments: uncertainty and munificence. Uncertainty refers to the extent to which future states of the environment can be anticipated or accurately predicted (Pfeffer and Salancik, 1978). Munificence refers to the extent to which an environment can support growth. Environments with greater munificence impose fewer constraints on organizations than those environments with resource constraints.

Both competence-enhancing and competence-destroying technological discontinuities generate uncertainty as firms struggle to master an incompletely understood product or process. Technological breakthroughs trigger a period of technological ferment as new technologies are tried, established price-performance ratios are upset, and new markets open. During these periods of technological upheaval, it becomes substantially more difficult to forecast demand and prices. Technological discontinuities, then, will be associated with increases in environmental uncertainty:

Hypothesis 3: Competitive uncertainty will be higher after a technological discontinuity than before the discontinuity.

Technological discontinuities drive sharp decreases in price-performance or input-output ratios. These factors, in turn, fuel demand in a product class. The role of technological progress in stimulating demand is well documented (e.g., Solow, 1957; Mensch, 1979). As both competence-enhancing and competence-destroying discontinuities reflect major price-performance improvements, both will be associated with increased demand and environmental munificence:

Hypothesis 4: Environmental munificence will be higher after a technological discontinuity than before the discontinuity.

Environments can also be described in terms of different competitive conditions (Scherer, 1980). Important dimensions of competitive conditions include entry-exit patterns and degree of order within a product class. Orderliness within a product class can be assessed by interfirm sales variability. Those environments with substantial net entry and substantial interfirm sales variability will be very different competitive arenas than those environments in which exits dominate and there is minimal interfirm sales variability.

Competence-destroying technological discontinuities have quite different effects on competitive conditions than competence-enhancing discontinuities. Competence-enhancing advances permit existing firms to exploit their competence and expertise and thereby gain competitive advantage over smaller or newer firms. Competence-enhancing discontinuities consolidate leadership in a product class; the rich get richer as liabilities of newness plague new entrants. These order-creating breakthroughs increase barriers to entry and minimum scale requirements. These processes will be reflected in relatively fewer entries relative to exits and a decrease in interfirm sales variability — those remaining firms will share more equally in product-class sales growth.

Competence-destroying discontinuities break the existing order. Barriers to entry are lowered; new firms enter previously impenetrable markets by exploiting the new technology (Astley, 1985; Abernathy and Clark, 1985). These discontinuities favor new entrants at the expense of entrenched defenders. New entrants take advantage of fundamentally different skills and expertise and gain sales at the expense of formerly dominant firms burdened with the legacy (i.e., skills, abilities, and expertise) of prior technologies and ways of operating (Astley, 1985; Tushman and Romanelli, 1985). Competence-destroying discontinuities will be associated with increased entry-to-exit ratios and an increase in interfirm sales variability:

Hypothesis 5: Competence-enhancing discontinuities will be associated with decreased entry-to-exit ratios and decreased interfirm sales variability. These patterns will be reversed for competence-destroying discontinuities.

If competence-destroying discontinuities do not emerge to alter a product class, successive competence-enhancing discontinuities will result in increased environmental orderliness and consolidation. Each competence-enhancing breakthrough builds on prior advances and further raises barriers to entry and minimum scale requirements. As product classes mature, the underlying resource base becomes ever more limited by physical and resource constraints. Successive competence-enhancing discontinuities will have smaller impacts on uncertainty and munificence as successive advances further exploit a limited technology and market-resource base:

Hypothesis 6: Successive competence-enhancing discontinuities will be associated with smaller increases in uncertainty and munificence.

Environmental changes induced by a technological discontinuity present a unique opportunity or threat for individual organizations (Tushman and Romanelli, 1985). Technological discontinuities alter the competitive environment and reward those innovative firms that are first to recognize and exploit technological opportunities. The superiority of a new technology presents organizations with a stark choice: adapt or face decline. Those firms that are among the first to adopt the new product or process proceed down the learning curve ahead of those that follow. The benefits of volume and experience provide early movers with a competitive edge not easily erased (Porter, 1985; MacMillan and McCaffrey, 1984). Therefore, we hypothesize:

Hypothesis 7: Those organizations that initiate major technological innovations will have higher growth rates than other firms in the product class.

RESEARCH DESIGN AND MEASURES

Three product classes were selected for study: domestic scheduled passenger airline transport, Portland cement manufacture, and minicomputer manufacture (excluding firms that merely add peripherals and/or software to another firm's minicomputer and resell the system). These three product classes represent assembled products, nonassembled products, and services; this product-class diversity increases the generalizability of our results. These industries were also selected because most participants historically had been undiversified, so environmental conditions outside the industry had little effect on these firms. Data on each product class was gathered from the year of the niche's inception (1872 for cement, 1924 for airlines, and 1956 for minicomputers) through 1980.

The three populations studied included all U.S. firms that produced cement, flew airplane passengers, or produced minicomputers. These industries were chosen partly because archival sources exist permitting a complete census of population members over time. Two outstanding books (Lesley, 1924; Davies, 1972) chronicle the history of the cement and airline industries and include meticulously researched profiles of early entrants into those product classes. In the airline industry, the Civil Aeronautics Board (CAB) lists of entries and exits after 1938 are definitive, due to licensing requirements. In cement, the very high degree of agreement among two trade journals and two industry directories from 1900 on suggests substantially all firms that ever produced cement are included. Similarly, in minicomputers, the very high degree of agreement among trade journals, an exhaustive annual industry directory in *Computers and Automation*, and International Data Corporation (IDC) product listings indicates that virtually all firms that ever produced a minicomputer are included. All sources included very small firms that survived only briefly; any firms that might have been overlooked in this study have never received published mention in three industries thoroughly covered by numerous archival sources.

Technological change. A thorough review of books and trade publications permitted the identification of price-performance changes and key technological events within the three product classes. Technological change was measured by examining key performance parameters for all new kilns, airplanes, or minicomputers introduced in each year of the industry's existence. For cement and airlines, percentage improvement in the state of the art was calculated by dividing the seat-mile-per-year or barrel-per-day capacity of the most capable plane or largest kiln in existence in a given year by the same capacity figure for the most capable plane or largest kiln in existence the previous year. This review of new equipment also permitted the identification of initiators and early adopters of significant innovations. Technological discontinuities were relatively easy to identify because a few innovations so markedly advanced the state of the art that they clearly stand out from less dramatic improvements.

The key performance parameter in cement production is kiln capacity in barrels of cement per day. For every new kiln, this capacity is reported by the manufacturer and is widely published in trade journals and industry directories. For airlines, the key economic factor is the number of passenger-seat-miles per year a plane can fly, calculated by multiplying the number of seats normally in an aircraft model by the number of miles per year it can fly at normal operating speeds for the average number of flight hours per year it proved able to log. These figures are reported in Davies (1972) for all aircraft models flown by U.S. airliners. In minicomputers, a key performance parameter is the amount of time required for the central processing unit to complete one cycle; this is the primary determinant of computer speed and throughput capability. Both *Computers and Automation*, a leading trade journal and industry directory, and the International Data Corporation (IDC), a leading computer-industry research firm, report cycle time for all minicomputers.

Uncertainty. Uncertainty is typically measured as a function of variance measures (Dess and Beard, 1984). Because environmental uncertainty refers to the extent to which future states of the environment cannot be predicted accurately, we measured uncertainty in terms of forecasting error — the ability of industry analysts to predict industry outcomes. Published forecasts for every SIC code are collected and indexed in *Predicasts Forecasts*. For each of the three niches, published one-year demand growth forecasts were collected and compared to actual historical results. Forecast error is defined as

$$\frac{(\ |\text{Forecast demand growth} - \text{Actual demand growth}|\ \text{X}\ 100)}{(\text{Actual demand growth})}$$

To measure environmental uncertainty, the mean forecast error for the five-year period before each technological discontinuity was compared to the mean forecast error for the five-year period following the discontinuity. The choice of five-year periods is arbitrary. Major technological changes do not have an overnight impact; it takes several years for their effect on uncertainty and munificence to appear. Yet in the longer run, extraneous events create demand fluctuations whose noise can drown out the patterns generated by major technological advances. Since the industries selected included discontinuities seven and ten years apart, five years was selected as the maximum practicable period of observation that would not create serious overlap problems between the era following one discontinuity and the era preceding another.

Munificence. Munificence was measured in terms of demand, the basic resource available to niche participants. Annual sales growth in units was obtained from the CAB and Bureau of Mines for the airline and cement niches, respectively. Minicomputer sales data were obtained from the International Data Corporation and from *Computers and Automation*. Since sales figures grow as a result of both inflation and growth in the economy as a whole, these factors were eliminated by dividing demand figures by an index of real GNP growth. Mean demand growth was calculated for five-year periods before and after each technological discontinuity.

Two possible objections may be raised to comparing the means of five-year periods preceding and following a discontinuity. First, if there is a strong upward trend in the time series, then for practically any year chosen, demand in the five succeeding years will be significantly higher than demand in the five preceding years. If this is so, there is nothing special about the eras surrounding a technological discontinuity. On the other hand, it may be that the findings are very sensitive to the exact year chosen to mark the discontinuity. If results are significant comparing, for example, 1960–1964 with 1965–1969, but not significant if the comparison is between 1959–1963 and 1964–1968, or between 1961–1965 and 1966–1970, then the finding is not robust.

Accordingly, the difference-of-means test was performed for every possible combination of two adjacent five-year periods for each industry. In each industry, it was found that eras of significant before and after demand shift are rare. Sixteen of 96 possible comparisons were significant at the .05 level in the cement industry (17 percent), 17 of 45 possible comparisons of airline demand (38 percent), and 2 of 7 possible comparisons of minicomputer demand (28 percent). This suggests that technological discontinuities are not the only events that seem to be associated with sharp increases in demand. However, neither do such shifts occur frequently or at random. In each case, a difference of one year either way in identifying the discontinuity would have made no difference; the demand shift is not particularly sensitive to the specific year chosen as the discontinuity.

Table 2

Summary of Variables, Measures, and Data Sources

Variable	Industry	Measure	Data Source	*N*	Range	Mean	SD
Technological change	Cement	% improvement in barrel/day production capacity of largest kiln.	Published specifications of new kilns in *Rock Products.*	90	0–320%		
	Airlines	% improvement in seat-miles per year capacity of most capable plane flown.	Davies (1972).	54	0–248%		
	Minicomputers	Central processor unit speed.	Published specifications in *Computers and Automation.*	24	.2–9000		
Locus of innovation	Cement	Proportion of new firms among earliest to adopt an innovation.	Reports on new kilns in *Rock Products* and trade directories.	4	.1–1.0		
	Airlines		Davies (1972), CAB annual studies of airplane purchases.	4	0–.9		
	Minicomputers		Published specifications in *Computers and Automation.*	3	0–.5		
Uncertainty	Cement	Mean percentage error of one-year demand growth forecasts	*Predicasts Forecasts.*	28	5.2–266.9	52.0	61.6
	Airlines			88	.1–381.4	59.2	58.4
	Minicomputers			36	3.5–811	138.1	167.1
Munificence	Cement	Annual cement consumption (tons).	U.S. Bureau of Mines.	101	8–85513	30296	27103
	Airlines	Annual passenger-seat-miles (mil.).	Civil Aeronautics Board.	52	.1–156.6	34.6	46.1
	Minicomputers	Annual minicomputer sales (000 units)	International Data Corporation.	16	.1–168	47.3	49.6
Entries	Cement	Number of firms producing for first time (mean, range and SD are entries per year, *N* is number of entries).	*Cement Industry Trade Directory; Rock Products.*	281	0–24	2.8	4.2
	Airlines		Davies (1972); CAB annual reports.	147	1–33	11.3	9.8
	Minicomputers		*Computers and Automation;* International Data Corporation.	173	3–30	10.8	7.3
Exits	Cement	Number of firms acquired or no longer producing (mean, SD and range are exits per year, *N* is number of exits).	*Cement Industry Trade Directory; Rock Products.*	218	0–23	2.2	3.9
	Airlines		Davies (1972); CAB annual reports.	126	1–28	9.7	8.2
	Minicomputers		*Computers and Automation;* International Data Corporation.	82	0–14	5.1	4.2
Interfirm sales variance	Airlines	Unweighted variance in five-year sales growth percentage among all firms in the industry.	Same as munificence measure.	4	2.0–13.4	5.5	4.6
	Minicomputers		Same as munificence measure.	4	2.6–21.3	11.2	8.6
Firm growth rate	Airlines	Firm sales at end of five-year era divided by sales at beginning of five-year era.	CAB annual reports.	46	−269–346	61.4	79.9
	Minicomputers		International Data Corporation.	67	−96–11900	635.6	1561.6

At a few comparatively rare periods in the history of an industry, then, one can locate a demand breakpoint, an era of two or three years during which average demand for the five years following any of these critical years significantly exceeds the average demand in the five years preceding the chosen year. Some of these critical eras are not associated with technological discontinuities. Without exception, every technological discontinuity is associated with such a demand shift.

Entry and exit. Entry and exit data were gathered from industry directories and books chronicling the histories of each product class. An entry was recorded in the year when a firm first began cement production, an airline flew its first passenger-mile, or a firm produced its first minicomputer. An exit was recorded when a firm ceased producing cement, flying passengers, or producing at least one minicomputer. Bankruptcy was recorded as an exit only if production ceased. An exit was recorded whenever a firm was acquired; an entry was recorded only if the acquiring firm did not already produce cement, fly passengers, or produce minicomputers. An entrant was classified as new if the company sold no products prior to its entry into the industry or as an existing firm if it sold at least one product before entering the industry. Entry and exit statistics are not calculated for the airline industry from 1938 through 1979, because entries were forbidden by the CAB, and exits depended more on regulatory action than on market forces. Table 2 provides measures, data sources, and summary data for each variable.

Early adopters. To test hypothesis 7, that those firms initiating technological discontinuities would have higher growth rates than other firms in the product class, we examined the growth rates of the first four adopters. Data were available for airlines after 1955 and for minicomputers. The number of early adopters chosen was arbitrary. Four were selected to provide a group large enough for a mean to be meaningful, yet small enough to argue reasonably that the firms considered were quicker to adopt the innovation than the rest of the industry.

RESULTS

Hypothesis 1 suggested that technological evolution would be characterized by periods of incremental change punctuated by either competence-destroying or competence-enhancing discontinuities. Hypothesis 2 argued that competence-destroying advances would be initiated by new entrants, while competence-enhancing advances would be initiated by existing firms. Table 3 summarizes the key technological discontinuities for each niche, while Figures 1a–1c provide more detailed data on key performance dimensions over time.

The cement, airline, and minicomputer niches opened in 1872, 1924, and 1956, respectively. After the three niche openings, there were six competence-enhancing technological discontinuities and two competence-destroying discontinuities (see Table 3). Each discontinuity had a marked effect on a key measure of cost or performance, far greater than the impact of other, more incremental technological events.[1]

Figure 1a documents the three significant technological changes that have punctuated the history of the Portland cement industry. Portland cement, invented in Europe, was first

[1] Other industries may not exhibit such marked differences and eventually a coefficient of technological progress could be developed to help distinguish incremental from discontinuous change; one approach might be to pool annual percentage improvements and select those more than two standard deviations above the mean.

Table 3

Significant Technological Discontinuities

Industry	Year	Event	Importance	Type of discontinuity	Locus of Innovation		Probability
					New firms	Existing firms	
Cement	1872	First production of Portland cement in the United States.	Discovery of proper raw materials and importation of knowledge opens new industry.	Niche opening	10 of 10	1 of 10	
	1896	Patent for process burning powdered coal as fuel.	Permits economical use of efficient rotary kilns.	Competence-destroying	4 of 5	1 of 5	.333
	1909	Edison patents long kiln (150 ft.).	Higher output with less cost.	Competence-enhancing	1 of 6	5 of 6	.001•
	1966	Dundee Cement installs huge kiln, far larger than any previous.	Use of process control permits operation of very efficient kilns.	Competence-enhancing	1 of 8	7 of 8	.000•
Airlines	1924	First airline.	Mail contracts make transport feasible.	Niche opening	9 of 10	1 of 10	
	1936	DC3 airplane.	First large and fast enough to carry passengers economically.	Competence-enhancing	0 of 4	4 of 4	.005•
	1959	First jet airplane in commercial use.	Speed changes economics of flying.	Competence-enhancing	0 of 4	4 of 4	.005•
	1969	Widebody jets debut.	Much greater capacity and efficiency.	Competence-enhancing	0 of 4	4 of 4	.005•
Minicomputer manufacture	1956	Burroughs E-101.	First computer under $50,000.	Niche opening	1 of 8	7 of 8	
	1965	Digital Equipment Corp. PDP-8.	First integrated-circuit minicomputer.	Competence-destroying	3 of 6	3 of 6	.019•
	1971	Data General Supernova SC.	Semiconductor memory much faster than core.	Competence-enhancing	0 of 7	7 of 7	.533

•$p < .01$.

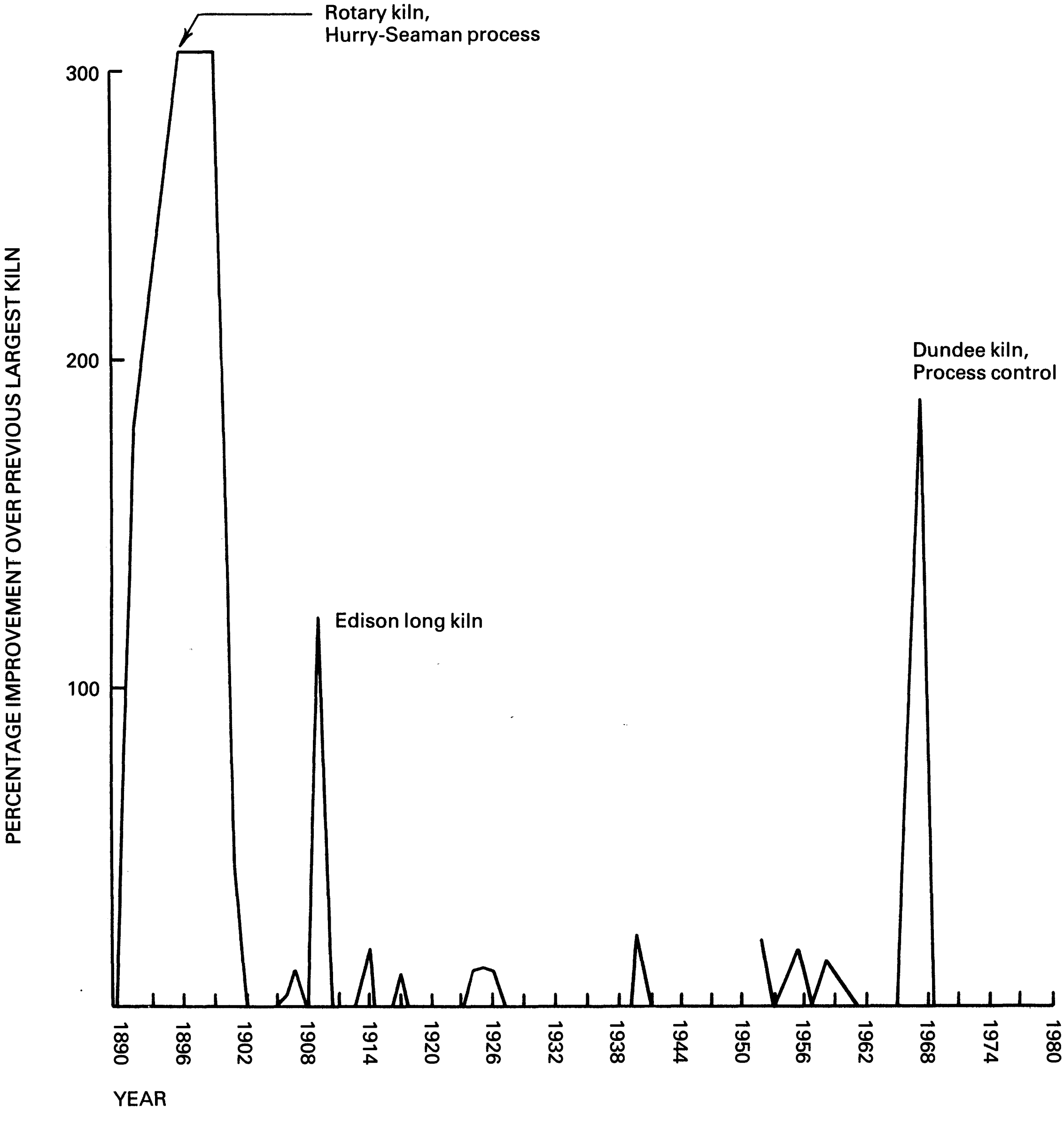
Note: Fisher's exact test compares the pool of firms that are among the first to enter the niche with the pool of firms that introduce or are among the first to adopt a major technological innovation. The null hypothesis is that the proportion of new firms is the same in each sample; probability is the probability of obtaining the observed proportions if the null hypothesis is correct.

made in this country about 1872, but early attempts to compete with established European brands were largely failures. Two events effectively established the domestic industry. The development of the rotary kiln made the manufacture of large volumes of cement with little labor practicable, and the invention in 1896 of a method for creating a continuous flame fed by powdered coal meant that a high-quality, uniform cement could be made without expensive hand-stoking.

During the following decade, rotary kilns 60 feet in length were standard. In 1909, Thomas Edison patented a technique for making kilns over 150 feet in length, enormously increasing the production capacity of a kiln, and the industry rapidly adopted the new "long kiln." Subsequent progress, though, was gradual; kiln capacity increased greatly over a period of decades, but in a series of incremental advances. In 1960, the industry began experimenting with computerized control of kilns. The introduction of computers permitted the construction of huge kilns, much larger than any that had preceded them. The experimental models of the early 1960s culminated in the enormous Dundee kiln in 1967; previously kilns of such capacity could not have been used because their huge size and weight made them impossible to regulate.

The revolution that brought powdered coal and rotary kilns to the industry was competence-destroying, rendering almost completely obsolete the know-how required to operate wood-fired vertical kilns. A totally new set of competences was required to make cement, and most vertical kiln operators went out of business. The Edison and Dundee kilns were competence-enhancing innovations; each markedly extended the capability of coal-fired rotary kiln technology. A large investment in new kilns and process-control equipment was required, but existing cement-making techniques were not made obsolete, and the leading firms in the industry proved most able to make the necessary capital expenditures.

Figure 1a. Barrels-per-day production capacity of the largest U.S. cement kiln, 1890–1980.

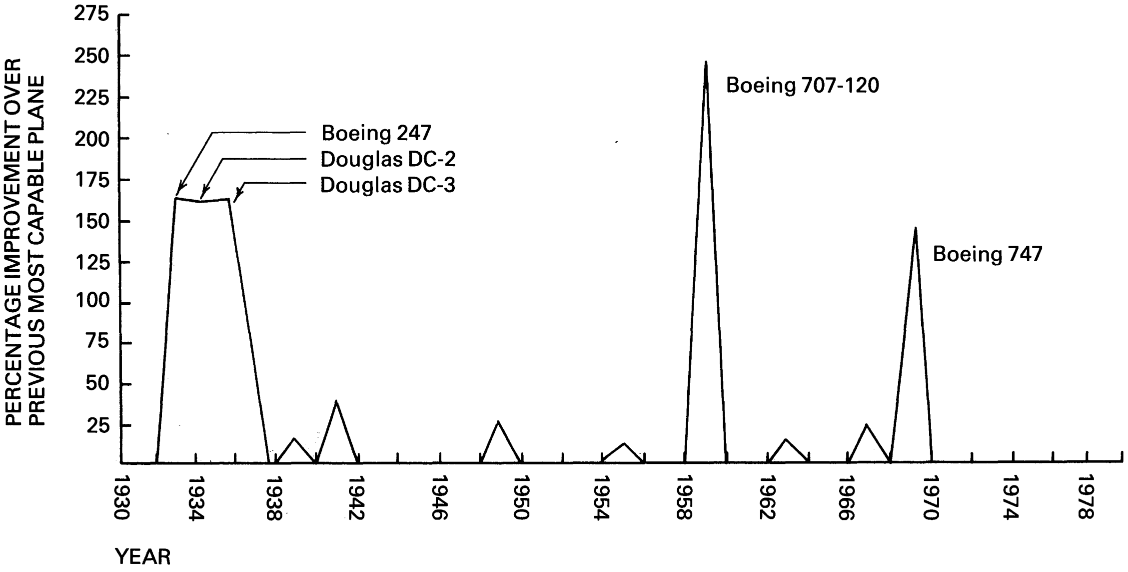


New developments in aircraft construction have been the major technological breakthroughs that have affected the economics of the airline industry, as illustrated in Figure 1b. Numerous flimsy, slow aircraft were flown until the early 1930s, when a flurry of development produced the Boeing 247, Douglas DC-2, and Douglas DC-3 in a span of three years, each a significant improvement on its immediate predecessor. The DC-3, which incorporated some 25 major improvements in aircraft design (Davies, 1972), superseded all other models to become so dominant that by the outbreak of World War II, 80 percent of U.S. airliners in service were DC-3s. Further aircraft improvements were incremental until 1959, when the debut of jet aircraft, with their considerably greater speed and size, again changed the economics of the airline industry. The final breakthrough event was the introduction in 1969 of the Boeing 747, beginning an era dominated by widebody jets.

All three of these major advances were competence enhancing from the perspective of the air carriers (though not from the perspective of aircraft manufacturers). Each advance generated significant economies of scale; airlines could carry many more passengers with each plane than was possible before. Though new skills were required to fly and maintain the new machines, airlines were able to build on their existing competences and take advantage of increased scale economies permitted with new aircraft.

In contrast to cement and airlines, in the minicomputer industry established firms built the first inexpensive computers (usually as an extension of their accounting machine lines). These early minicomputers were based on vacuum tubes and/or transistor technology. The first transistor minicomputer was far faster than its vacuum-tube predecessors, but transistor architecture was replaced by integrated circuitry within two years and thus never diffused widely. Sales were meager until integrated-

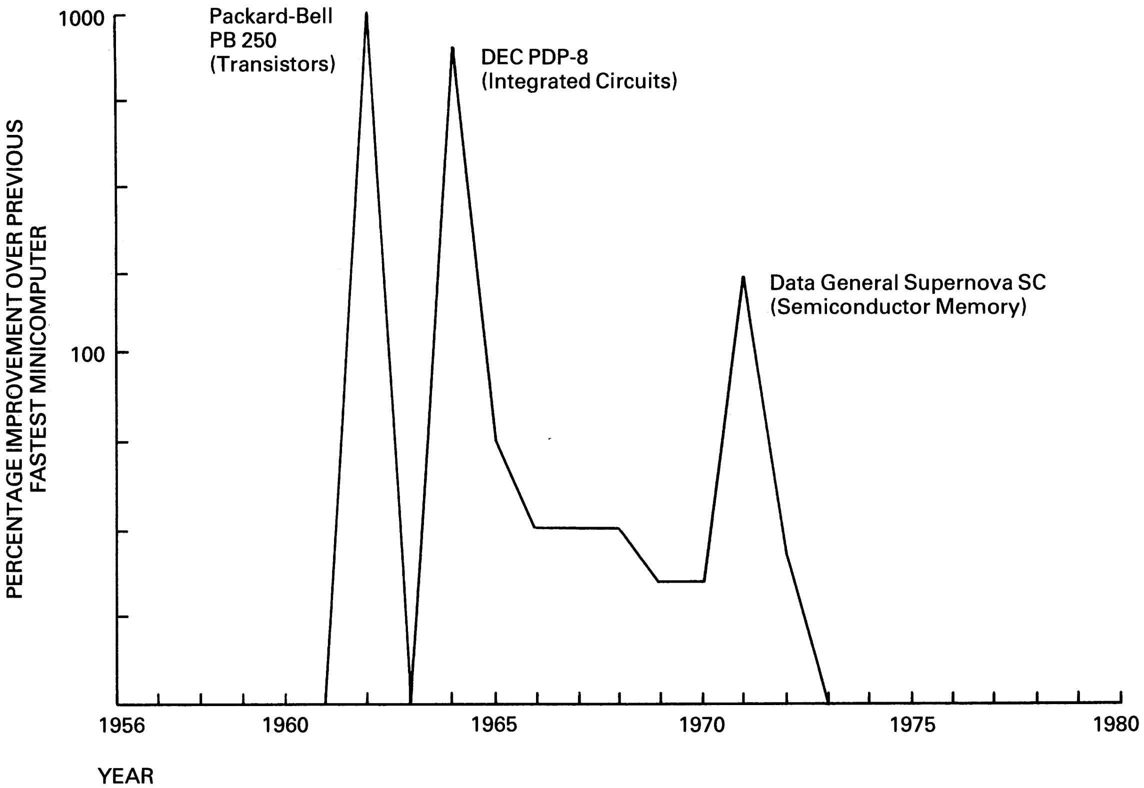
Figure 1b. Seat-miles-per-year capacity of the most capable plane flown by U.S. airlines, 1930–1978.



circuit minicomputers were introduced by a combination of new and older firms. Figure 1c depicts the enormous impact of transistors, immediately followed by integrated circuitry, on computer performance. Integrated circuitry increased minicomputer speed more than 100 times between 1963 and 1965, while size and assembly complexity also decreased substantially. Integrated circuits permitted the construction of compact machines at a greatly reduced cost by eliminating most of the wiring associated with transistors. Integrated-circuit technology was competence-destroying, since expertise in designing, programming, and assembling transistor-based computers was not especially transferable to the design and manufacture of integrated-circuit machines (Fishman, 1981).

The introduction of semiconductor memory in 1971 caused another abrupt performance improvement (see Figure 1c) but did not challenge the fundamental competence of existing minicomputer firms; most companies were able to offer customers versions of their existing models equipped with either magnetic core or semiconductor memory. The effect of semiconductor memory was to increase order in the product class as existing firms were able easily to incorporate this innovation into their existing expertise. For memory manufacturers, however, semiconductor memory was a competence-destroying discontinuity.

Figure 1c. Central-processor-unit cycle time of the fastest minicomputer in production, 1956–1980.



Note: The vertical scale is logarithmic, because the impact of transistors and integrated circuitry on processor speed was so great.

These patterns of incremental technological progress punctuated by discontinuities strongly support hypothesis 1. As suggested in hypothesis 2, the locus of technological innovation for competence-enhancing breakthroughs significantly differs from that of competence-destroying discontinuities. The first cement and airline firms were overwhelmingly new start-ups, not existing companies entering a new industry (Table 3). No product classes existed in 1872 or 1924 whose competences were transferable to cement manufacture or flying airplanes. In contrast, early minicomputers were made by existing accounting machine and electronics manufacturers, who found their existing know-how was readily transferable to the first small, crude computers. New industries can be started either by new organizations or by established ones from other industries; a key variable seems to be whether analogous product classes with transferable competences exist when a new product class emerges.

Patterns in the locus of innovation for discontinuities subsequent to product-class openings are remarkably consistent. The two competence-destroying discontinuities were largely pioneered by new firms (i.e., 7 of 11), while the six competence-enhancing discontinuities were almost exclusively introduced by established industry members (i.e., 35 of 37 firms were existing firms; Fisher's exact test; $p = .0002$). Across these three industries, competence-destroying breakthroughs are significantly more likely to be initiated by new firms, while competence-enhancing breakthroughs are significantly more likely to be initiated by existing firms. Similarly, within each industry, Fisher's exact tests indicate that the proportion of new firms that initiate competence-destroying discontinuities is significantly greater than the proportion of new firms initiating competence-enhancing discontinuities (see last column in Table 3).

Hypothesis 3 suggested that environmental uncertainty would be significantly higher after a technological discontinuity than before it. Since the forecasts we used to test this hypothesis are not available before 1950, only four of the eight technological discontinuities could be tested. In three of the four cases examined, mean forecast error after the discontinuity was significantly higher ($p < .05$) than before the discontinuity (see

Table 4

Forecast Error over Time*

Industry	Era	Mean forecast error	$t(1)$	D.f.	$t(2)$	D.f.
Airlines	1955–1959 1960–1964	16.15% 77.81%	1.78•	18		
Airlines	1965–1969 1970–1974	18.52% 49.13%	4.35••	66	1.91•	54
Cement	1963–1967 1968–1972	38.31% 80.26%	1.85•	26		
Minicomputers	1967–1971 1972–1976	146.31% 136.12%	–.14	34		

•$p < .05$; ••$p < .01$.

*$t(1)$ compares mean forecast error of the first period to the mean forecast error of the second period; $t(2)$ compares 1960–1964 with 1970–1974.

Table 4). Except for the period following the introduction of semiconductor memory in minicomputers, the ability of experienced industry observers to predict demand one year in advance was significantly poorer following technological disruption than before.[2] In the semiconductor case, forecast errors were very high both before and after the discontinuity.

Hypothesis 4 suggested that environmental munificence would be higher after a technological discontinuity than before it. The results in Table 5 strongly support the hypothesis. In every case, demand growth following the discontinuity was significantly higher than it was immediately prior to the discontinuity. Further, these demand data indicate the enormous impact of initial discontinuities on product-class demand. Initial discontinuities were associated with, on average, a 529-percent increase in product-class demand. Subsequent discontinuities spark smaller (though still relatively large) increases in demand (226 percent, on average). Technological discontinuities were, then, associated with significantly higher demand after each discontinuity; this effect, though significant in each case, was smaller over successive discontinuities (except for minicomputers, where demand increased substantially after both technological discontinuities).

Table 5

Demand before and after Technological Discontinuity

Industry	Era	Mean annual demand	t*
Cement	1892–1896	168	–3.16••
	1897–1901	1249	
	1905–1909	9271	–6.35••
	1910–1914	15612	
	1963–1967	63348	–2.16•
	1968–1972	77122	
Airlines	1932–1936	2326	–3.01••
	1937–1941	8019	
	1955–1959	244625	–3.68••
	1960–1964	355678	
	1965–1969	742838	–4.42••
	1970–1974	1165943	
Minicomputers	1960–1964	435	–1.96•
	1965–1969	2181	
	1967–1971	7274	–4.60•
	1972–1976	47149	

•$p < .05$; ••$p < .01$.

*t-statistic compares mean demand of first period with mean demand of second period. In each case, there are 8 degrees of freedom.

Hypothesis 5 argued that competence-enhancing discontinuities would be associated with decreased entry-to-exit ratios and decreased interfirm sales variability. Opposite effects were hypothesized for competence-destroying discontinuities. Entry-to-exit ratios were calculated for five years before and after each discontinuity (except for the 1938–1979 period in airlines). Results in Table 6 are partially supportive of hypothesis 5. The ratio of entries to exits was higher in each of the five years before a competence-enhancing discontinuity than during the five subsequent years. None of the differences is statistically significant, though pre-discontinuity entry-to-exit

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[2] Since data on published forecasts, annual growth in demand, and entry and exit data are available for the three populations, sampling error is not an issue; one could simply report the differences between populations. However, the critical question here is whether consistent differences between pre- and post-discontinuity environments can be discerned. The significance tests show that the probability is small that chance processes could have produced the reported differences between pre- and post-discontinuity eras (Blalock, 1979: 241).

ratios range from 1.15 to over 7 times greater than post-discontinuity entry-to-exit ratios. Entry-to-exit ratios prevailing before a discontinuity are markedly shifted in favor of exits following competence-enhancing discontinuities.

It was expected that entry-to-exit ratios would rise following the two competence-destroying discontinuities; the opposite was observed. Entry-to-exit ratios were quite high following these competence-destroying innovations but were smaller than the extremely large entry-to-exit ratios prevailing just before the discontinuity. Many firms entered and few departed the cement and minicomputer niches in the 1892–1896 and 1960–1964 periods, respectively. Both of these eras were themselves periods of technological ferment in emerging product classes – rotary kilns began to replace vertical kilns in the early 1890s, and transistors began to replace vacuum tubes in the early 1960s. It may be that the rush of new firms to enter emerging product classes confounds the effects of competence-destroying discontinuities.

Table 6

Entry-to-Exit Ratio before and after Discontinuity

Industry	Era	Entry-to-exit ratio*	Discontinuity type
Cement	1872–1896	3.25	Niche opening
	1892–1896	46.00	Competence-destroying
	1897–1901	12.00	
	1905–1909	1.489	Competence-enhancing
	1910–1914	.814	
	1963–1967	1.250	Competence-enhancing
	1968–1972	.160	
Airlines	1913–1930	1.730	Niche opening
	1930–1934	.820	Competence-enhancing†
	1935–1939	.714	
Minicomputers	1956–1960	Not finite‡	Niche opening
	1960–1964	5.500	Competence-destroying
	1965–1969	2.917	
	1967–1971	4.933	Competence-enhancing
	1972–1976	2.708	

*The difference between the pre-discontinuity entry-to-exit ratios and the corresponding post-discontinuity entry-to-exit ratios, while consistent, do not reach statistical significance, due to the large variance between individual years.

†Airline data for subsequent periods were not reported, because entry and exit were regulated.

‡Six entries, no exits.

Entry-to-exit patterns are consistent across these three divergent industries. Entries dominate exits early on, reflecting the rush of new entrants. After competence-enhancing discontinuities in cement and airlines, exits dominate entries, reflecting industry consolidation. In minicomputers, while entry-to-exit ratios decrease over time, entries dominate exits throughout this 20-year period.

Hypothesis 5 also suggested that competence-enhancing discontinuities would decrease interfirm sales variability as those remaining firms adopt industry standards in both products and processes. Small firms drop out of the industry, entry barriers are raised, and firms exploiting similar existing competences experience relatively similar outcomes. Following competence-destroying discontinuities, though, we expected marked variability in sales growth as firms compete with each other on fundamentally different bases; some firms' sales grow explosively while others experience dramatic sales decline.

The results in Table 7 for airlines and minicomputers support this prediction. In minicomputers, integrated circuits triggered explosive growth in the product class and increased interfirm sales variability. Following the other three competence-enhancing discontinuities, though, interfirm sales variability decreased significantly; niche occupants experienced similar results as they built on their existing competences to exploit demand growth.

Table 7

Interfirm Sales Variability before and after Discontinuity

Industry	Era	Discontinuity type	Interfirm variance	*F**	D.f.
Airlines	1955–1959	Competence-enhancing	79.24	2.726•	12,12
	1960–1964		29.07		
	1965–1969	Competence-enhancing	103.63	4.096••	11,11
	1970–1974		25.30		
Minicomputers	1960–1964	Competence-destroying	5599.32	–17.480••	8,11
	1965–1969		97873.25		
	1967–1971	Competence-enhancing	86.26	9.960••	9,35
	1972–1976		8.65		

•$p<.05$; ••$p<.01$.

*The *F*-statistic compares the ratio of interfirm sales variance before the discontinuity to interfirm sales variance after the discontinuity.

Hypothesis 6 suggested that successive competence-enhancing discontinuities would be associated with relatively smaller effects on uncertainty and munificence. Because forecast data are not available before 1950, this hypothesis could only be partially tested in the case of uncertainty. As predicted, the mean forecast error in airlines for the 1960–1964 period is higher than that for the 1970–1974 period ($t = 1.91$; $p < .05$; see Table 4). Hypothesis 6 receives stronger support with respect to munificence. In cement and airlines, mean growth rates in demand are smaller for each successive competence-enhancing discontinuity. These differences are significant for two of the three comparisons (see Table 8). These data suggest that as technology matures, successive competence-enhancing discontinuities increase both uncertainty and munificence, but not as much as those discontinuities that preceded them in establishing the product class. These data, as well as those entry-to-exit data in Table 6, suggest that successive competence-enhancing advances result in increased product-class maturity, reflected in decreased uncertainty, decreased demand growth-rates, and increased product-class consolidation.

Hypothesis 7 argued that those firms initiating technological discontinuities would have higher growth rates than other firms in the product class. Table 9 compares five-year growth rates for the four early adopters to all other firms before and after

Table 8

Demand Patterns Following Successive Competence-Enhancing Discontinuities

Industry	Era	Mean growth*	$t(1)$	D.f.
Cement	1910–1914	48.3%	12.03••	8
	1968–1972	8.4%		
Airlines	1937–1941	161.5%		
	1960–1964	33.4%	30.79••	8
	1970–1974	32.3%	.75	8

••$p < .01$.

*Mean growth is the average annual *percentage* gain in sales for the industry (in contrast to Table 5, which measures demand in units). The t-statistic compares consecutive post-discontinuity periods; e.g., a comparison of mean percentage growth for 1910–1914 with mean percentage growth for 1968–1972 yields a t-statistic of 12.03, failing to support the null hypothesis that there is no difference in percentage growth rates between successive post-discontinuity eras.

technological discontinuities. As hypothesized in each of the four comparisons, early adopters experienced more growth than other firms. Early adopters had significantly higher five-year growth rates than other firms in the airline industry. For jets, early adopters had growth rates similar to others before the discontinuity, while for widebody jets, the early adopters had higher sales growth before and after the discontinuity (see Table 9). In minicomputers, early adopters had annual percentage growth rates that were 105 percentage points higher, on average, than other firms. Technological discontinuities are, then, sources of opportunities (or threats) for firms. While dominant technologies cannot be known in advance, those firms that recognize and quickly adopt a technological breakthrough grow more rapidly than others.

Table 9

Relative Sales Growth of First Four Adopters of a Major Innovation

Industry	Innovation*	Era	Mean sales growth first 4 adopters	Growth all others	t†	D.f.
Airlines	Jet aircraft	1955–1959	38.1%	22.2%	1.268	10
		1960–1964	44.3%	12.3%	2.121••	10
	Widebody jets	1965–1969	101.1%	19.2%	2.487•	9
		1970–1974	16.1%	1.0%	2.642•	9
Minicomputer	Integrated circuits	1960–1964	Not available (new firms)			
		1965–1969	339.2%	179.6%	.44	10
	Semiconductor memory	1967–1971	Not available (new firms)			
		1972–1976	238.0%	188.4%	.14	34

•$p < .05$; ••$p < .06$.

*The first four adopters in each case are: *Jet aircraft:* American, TWA, United, Eastern; *Widebody jet:* American, TWA, Continental, United; *Integrated circuits:* Digital Equipment, Computer Control Co., Scientific Data Systems, Systems Engineering Laboratories; *Semiconductors:* Data General, Digital Computer Controls, Interdata, Microdata.

†The t-test compares the mean annual percentage growth rates of the four firms who first introduced or adopted each innovation with the mean annual percentage growth rates of all other firms in the industry. Two periods do not yield interpretable statistics because annual growth for new firms cannot be calculated when the base year contains zero sales.

DISCUSSION

The purpose of this paper has been to explore technological evolution and to investigate its impact on environmental conditions. A better understanding of technological evolution may increase our understanding of a range of phenomena at the population (e.g., structural evolution, population dynamics, strategic groups) as well as the organizational levels of analysis (e.g., organizational adaptation, executive succession patterns, executive demographics, and political dynamics) (Astley, 1985; Tushman and Romanelli, 1985).

Longitudinal data across three diverse industries indicate that technology evolves through relatively long periods of incremental change punctuated by relatively rare innovations that radically improve the state of the art. Such discontinuities occurred only eight times in the 190 total years observed across three industries. Yet in each product class, these technological shifts stand out clearly and significantly altered competitive environments.

The effect of major technological change on the two fundamental dimensions of uncertainty and munificence is unambiguous. Environmental conditions following a discontinuity are sharply different from those that prevailed before the technical breakthrough: the advance makes available new resources to fuel growth within the niche and renders observers far less able to predict the extent of future resource availability. Major technical change opens new worlds for a product class but requires niche occupants to deal with a considerable amount of ambiguity and uncertainty as they struggle to comprehend and master both the new technology and the new competitive environment.

It is also clear that technological discontinuities are not all alike. Competence-enhancing discontinuities significantly advance the state of the art yet build on, or permit the transfer of, existing know-how and knowledge. Competence-destroying discontinuities, on the other hand, significantly advance the technological frontier, but with a knowledge, skill, and competence base that is inconsistent with prior know-how. While competence-enhancing discontinuities build on existing experience, competence-destroying discontinuities require fundamentally new skills and technological competence.

The locus of innovation and the environmental consequences of competence-destroying versus competence-enhancing discontinuities are quite different. Competence-enhancing breakthroughs are overwhelmingly initiated by existing, successful firms. Competence-enhancing discontinuities result in greater product-class consolidation, reflected in relatively smaller entry-to-exit ratios and decreased interfirm sales variability. As competence-enhancing discontinuities build on existing know-how, it appears that the rich get richer, while new firms face liabilities of newness (Stinchcombe, 1965). Product-class conditions become ever more consolidated over successive order-creating discontinuities.

Competence-destroying discontinuities are more rare than competence-enhancing technological advances. Competence-destroying breakthroughs are watershed events in the life of a product class; they open up new branches in the course of industrial evolution (Astley, 1985). These discontinuities are initiated by new firms and open up the product class to waves of new entrants unconstrained by prior technologies and organizational inertia. While liabilities of newness plague new firms confronting competence-enhancing breakthroughs, liabilities of age and tradition constrain existing, successful firms in the face of competence-destroying discontinuities. Although the data were limited, competence-destroying discontinuities seem to break the grip of established firms in a product class. Interfirm sales variability jumped after integrated circuits were introduced in minicomputers, as new firms and established firms pursued different strategies, with markedly different results. Similarly in cement, new firms initiated rotary kilns and went on to dominate the industry.

These patterns are seen most vividly in minicomputer manufacture. The first inexpensive computers were built by established office-equipment firms (e.g., Monroe), electronics firms (e.g., Packard-Bell), and computer firms (e.g., Burroughs). This new product class continued unchanged until the advent of integrated circuits. Without exception, established firms floundered in the face of a technology based on active components. Integrated circuits rendered obsolete much of the engineering knowledge embodied in the first minicomputers. Office-equipment and the existing computer firms were unable to produce a successful model embodying semiconductor technology. Only the few firms explicitly founded to make minicomputers (e.g., DEC) were able to make the transition. By 1965, almost every firm that produced early minicomputers had exited the product class.

Technological discontinuities, whether competence-destroying or competence-enhancing, appear to afford a rare opportunity for competitive advantage for firms willing to risk early adoption. In all four cases, early adopters of major innovations had greater five-year growth rates than the rest of the product class. While these data are not unequivocal, firms that recognize and seize opportunities presented by major advances gain first-mover advantages. Those firms that do not adopt the innovation early or, worse, increase investment in obsolete technology, risk failing, because product-class conditions change so dramatically after the discontinuity.

Technological advance seems to be an important determinant of market as well as intraorganizational power. Competence-enhancing discontinuities are order creating in that they build on existing product-class know-how. These breakthroughs increase the market power of existing firms as barriers to entry are raised and dependence on buyers and suppliers decreases in the face of larger and more dominant producers. Competence-destroying technological advances, on the other hand, destroy order in a product class. These discontinuities create fundamental technological uncertainty as incompatible technologies compete for dominance. New firms, unconstrained by prior competence and history, take advantage of technological opportunities and the lethargy of organizations burdened with the consequences of prior success. Given the enormous impact of technological advance on product-class order, future research could explore the politics of technological change as interest groups attempt to shape technological progress to suit their own competences (e.g., Noble, 1984).

Within the firm, technological discontinuities affect the distribution of power and, in turn, decision-making processes. Those who control technological advances (whether competence destroying or enhancing) will gain power at others' expense (e.g., Morison, 1966; Pettigrew, 1973). Because technological dominance is rarely known in advance, the control of technological assumptions and the locus of technological decisions will be an important arena for intraorganizational political processes. Shaping technological advance may be a critical organizational issue, since technology affects both intra- and interorganizational bases of power.

Because technology affects organizational adaptation, organizations may be able to use investment in R&D and technological innovation to shape environmental conditions in their favor. While technological dominance cannot be predicted at the outset (e.g., Wankel engines, bubble memory), organizations that create technological variation, or are able to adopt technological change quickly, maximize their probability of being able to move with a changing technological frontier. Organizations that do not contribute to or keep up with multiple technological bases may lose their ability to be aware of and deal with technological evolution (Dutton and Thomas, 1985).

The patterns of technological change are similar across these three diverse industries. It appears that new product classes are associated with a wave of new entrants, relatively few exits, and substantial technological experimentation. Competence-destroying discontinuities occurred early in both cement and minicomputer manufacture. After competence-destroying breakthroughs, successive competence-enhancing discontinuities resulted in an ever more consolidated and mature product class. While we have no data, subsequent competence-destroying discontinuities may, in turn, break up a mature product class and restart the product class's evolutionary clock (e.g., microcomputers vs. minicomputers or compact disks vs. records).

Competence-destroying discontinuities initiate a period of technological ferment, as alternative technologies compete for dominance. This period of technological competition lasts until a dominant design emerges as a synthesis of prior technological experimentation (e.g., Dundee kiln, DC-3, PDP-11). Dominant designs reflect a consolidation of industry standards. These designs crowd out alternative designs and become guideposts for incremental product as well as major process change (Utterback and Abernathy, 1975). Thus, quite apart from major technological advance, the establishment of a dominant design may also be an important lever in shaping environmental conditions and organizational fate.

CONCLUSION

While these data indicate that technological discontinuities exist and that these discontinuities have important effects on environmental conditions, the data are not conclusive. Though the data are consistent across three diverse industries, the number of cases is relatively small, and some of the tests were limited by data availability. Future research needs to focus more closely on patterns of technological change. If technology is an important determinant of competitive conditions, we need to know more about differences between competence-destroying and competence-enhancing technological advances, what distinguishes between incremental improvements and dramatic advances, what are dominant designs and how they occur, and what are the impacts of competence-destroying advances in mature product classes.

Both product and process innovation are important. While the data here are only suggestive, it may be that different kinds of innovation are relatively more important in different product classes. For nonassembled products (e.g., cement, glass, oil), major process innovations may be relatively more important than product innovations. For assembled products (e.g., minicomputers, VCRs, scientific instruments), major product improvements or substitutions may be relatively more important than process innovations. Future research might explore the differential importance of major product and process innovations by different product-class type.

The effects of nontechnological discontinuities must also be examined to understand more fully how competitive environments change. Technological change does not occur in a vacuum. If frequently sparks a response from the legal, political, or social environments. For example, bioengineering, automatic control machinery, nuclear power, and supersonic transportation each has been directly affected by a complex set of interactions among technological and political, social, and legal considerations (e.g., Horwitch, 1982; Astley and Fombrun, 1983; Noble, 1984). Further, periods of incremental technological change and standardization may become turbulent for nontechnological reasons (e.g., airline deregulation or the outlawing of basing-point pricing in cement). More complete analyses of the technology-environment linkages must also take into account the linkages between technological change and these other important social, political, and legal forces.

Technological change clearly affects organizational environments. Beyond exploring more deeply the nature of technological change, future research could also explore the linkage between technological evolution and population phenomena, such as structural evolution, mortality rates, or strategic groups, as well as organizational issues, such as adaptation, succession, and political processes. These results suggest that technology is not a static environmental resource. Rather, technology advances through the competition between alternative technologies promoted by rivalrous organizations. At the organization level, technological action, such as investment in R&D and internal venturing, may be a powerful lever in directly shaping environmental conditions and, in turn, organizational adaptation.

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