Managing Through Cycles of Technological Change
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MANAGING THROUGH CYCLES OF TECHNOLOGICAL CHANGE

Four lessons are drawn from the evidence that technology progresses in a series of cycles, hinging on discontinuities and the emergence of dominant designs.

Philip Anderson and Michael L. Tushman

> *"... industrial mutation ... incessantly revolutionizes the economic structure from within. This process of Creative Destruction is the essential fact about capitalism."* —**Josef Schumpeter,** *1942.*

We are managing in what Peter Drucker has termed "the age of discontinuity." Examples of revolutionary technological changes that transform industries abound. Ceramic engine parts will replace metal engine parts in the next decade, thanks to their high strength-to-weight ratio and resistance to heat. Flat-screen displays will obsolesce today's bulky cathode-ray tubes in television screens and computer monitors. Optical disks capable of storing billions of bytes will supplant today's magnetic fixed disks for mass computer storage. Lithium batteries will supersede today's lead-acid technology.

It is precisely this sort of discontinuous change that brings about "creative destruction," the overturning of established industry structures which Schumpeter saw as the fundamental engine of capitalist progress. Building on a tradition extending back to the 1950s (see for example Strassmann, 1956, and Bright, 1964), Richard Foster (1986) argues that industry leaders become losers because they have difficulty managing technological discontinuities—movements from one technology to another with inherently higher limits.

Examples of creative destruction based on both product and process revolutions abound: the shift from vacuum tubes to semiconductors overturned the dominance of firms such as RCA and Sylvania; with the installation of new, energy-saving cement manufacturing technology, eight of the ten largest American cement makers were acquired by foreign firms between 1973 and 1980.

Managing through periods of upheaval and transformation requires that we develop a useful model of technological change. Are there predictable patterns of innovation that recur time and time again in industry after industry? Are there predictable consequences of technological discontinuities? Who pioneers discontinuous innovations. When do leaders become losers?

Foster's depiction of technological progression through a series of S-curves suggests that technological change follows a cyclical pattern. The best-known model of technological change, the Abernathy/Utterback model, originally viewed technological progress as a single cycle, leading toward more process and less product innovation and culminating in the "productivity dilemma." Yet more recent updates of this framework in the early 1980s also conclude that technological change is cyclical—"dematurity" can in effect set the clock back and return an industry from a "specific" to a "fluid" state.

Our study of the entire history of three industries (see editorial box, next page) leads us to conclude that technology progresses in a series of cycles, hinging on technological discontinuities and the emergence of dominant designs. Here, we discuss:

- The cyclical nature of technological change.
- The influence of "competences."
- The empirical character of observed technology cycles.
- Who pioneers discontinuities and dominant designs.
- The process of "creative destruction."
- The implications of technology cycles for managers.

Technology Cycles

As Foster's notion of a series of S-curves suggests, an industry evolves through a *succession* of technology cycles. Each cycle begins with a *technological discontinuity*. Discontinuities are breakthrough

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How the Study Was Conducted

Lehigh University's Center for Innovation Management Studies and Columbia University's Strategy Research Center funded our three-year investigation of the entire history of the U.S. minicomputer, cement and glass (containers, plate and windows) industries. We tracked the entry and exit of firms in these industries from their inception via directories extensively cross-checked with archival sources and data from trade associations and consultants. We also tracked a single key performance measure for each industry to empirically identify discontinuities: we focused on kiln capacity for cement, machine capacity for glass containers and flat glass, and CPU speed for minicomputers. To measure dominant design, we looked at new process installations for glass and cement and sales by model for minicomputers. A dominant design was considered to have emerged when one fundamental architecture accounted for 50 percent or more of new product sales or process installations for three straight years. Complete details of the data sources, methodology, and statistical analyses performed are contained in Anderson (1988), available from University Microfilms.

Important limitations to the study should be noted. First, due to the length of the time series examined, only three industries are included; it would be unwise to over-generalize the results. In particular, these findings may not completely apply to service industries or sectors where an oligopoly exists, where regulation is an important factor, or where strong patent positions are common. Furthermore, the study looked at only one performance measure per industry (due to limitations of historical data); in most industries, one would measure the technical frontier using several parameters. We were only able to examine survival and exit rates; the study draws no conclusion about the effect on firm performance of being first-to-innovation or first-to-standard.—**P.A. and M.T.**

innovations that advance by an order of magnitude the technological state-of-the-art which characterizes an industry. They are based on new technologies whose technical limits are inherently greater than those of the previous dominant technology, along economically relevant dimensions of merit.

To illustrate, examine Figure 1. The manufacture of window glass has been characterized by three great discontinuities. In the 19th century, skilled artisans blew molten glass into long cylinders, which were cut with a wire and flattened into glass sheets. In 1903, the Lubbers process substituted an automatic blowing machine for the artisan. In 1917, the Colburn machine, which drew a continuous ribbon from a tank of molten glass, was introduced. In 1963, the Pilkington float glass process was introduced in the United States, producing a continuous ribbon by floating molten glass across a bed of molten alloy. In each case, a process with inherently higher limits redefined the state of the art, increasing machine capacity by an order of magnitude while lowering costs and improving quality.

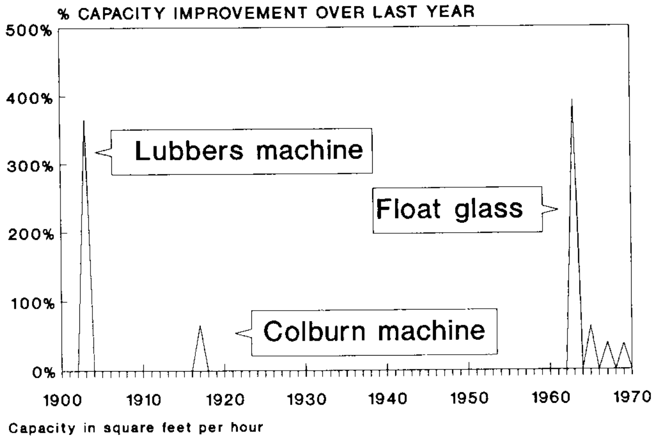

Figure 1.—Three great discontinuities mark the development of machinery for manufacturing window glass in the United States.

Each technological discontinuity inaugurates a *technology cycle* (Figure 2). The breakthrough initiates an *era of ferment,* characterized by two processes. First, the new technology displaces its predecessor during an *era of substitution.* Though Foster argues that new technologies appear only when the old technology reaches its technical limits, often the older technology improves markedly in response to the competitive threat. Gaslight technology, for example, improved dramatically in the decade after the introduction of the Edison electric light; Apple has pushed the limits of 8-bit microcomputer technology forward dramatically since the appearance of 16-bit and 32-bit replacements for the once-dominant Apple II. Despite these improvements, Fisher and Pry (1971) demonstrate that in many cases, the substitution process proceeds with mathematical inevitability once a small initial penetration is achieved.

The second process partly overlaps the first. An era of *design competition* follows a discontinuity. Radical innovations are usually crude, and are replaced by more refined versions of the initial product or process. Typically, several competing designs emerge, each embodying the fundamental breakthrough advance in a different way. Examples include the tremendous proliferation of automobile designs following Duryea's first auto, or the appearance of dozens of competing airplane models after the Wright brothers' invention.

The design competition culminates in the appearance of what Abernathy and Utterback (1978) term a "dominant design," also called a "technological guidepost" by Sahal (1981). This design is a single basic architecture that becomes the accepted market standard. Dominant designs are not necessarily better than competing designs, and they often pioneer no innovative features themselves. Rather, they represent a *combination* of features, often pioneered elsewhere, that sets a benchmark to which all subsequent designs are compared. Examples include the IBM 360 computer series, the Fordson tractor, and the Ford Model T automobile.

The emergence of a dominant design marks the end of the era of ferment and the beginning of a period of incremental change. Here, the rate of design experimentation drops sharply, and the focus of competition shifts to market segmentation and lowering costs (via design simplification and process improvement). Many scholars and R&D managers contend that it is the patient accumulation of small improvements that accounts for the bulk of technological progress. Though this may not be true in every case, there is little doubt that once a design becomes a standard, it establishes a trajectory for future technical progress and changes the basis of competition in the industry. This era of competition based on slight improvements on a standard design continues until the next technological discontinuity emerges to kick off a new technology cycle.

Influence of "Competences"

The nature of the technology cycle is dramatically affected by the cutting dimension of *competence*. Some discontinuous innovations are *competence-destroying*. They obsolesce existing knowhow; mastery of the old technology does not imply mastery of the new. Firms must embark on a new learning curve which is essentially unaffected by the firm's existing knowhow, and technical professionals require new training. The transistor illustrates a competence-destroying product innovation; mastery of vacuum tube technology proved as much a hindrance as a help to engineers trying to understand semiconductor electronics, and the learning curve for firms struggling to master the technology was unaffected by the firm's vacuum tube knowhow.

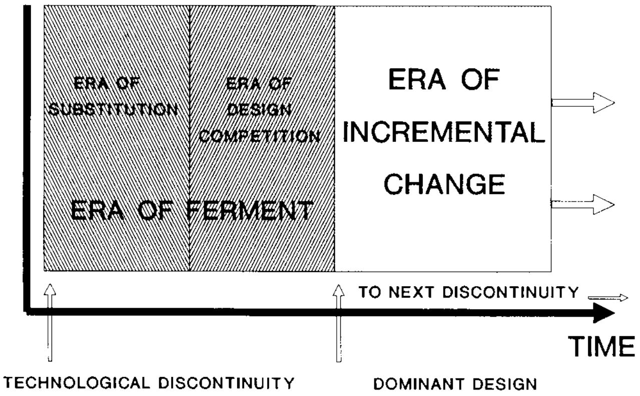

Figure 2—Industries evolve through successions of technology cycles, each inaugurated by a technological discontinuity.

Inability to adapt to a new technical order seems to kill more firms than the inability to withstand a recession.

Similarly, float glass is a competence-destroying process discontinuity; a firm's knowledge of Colburn drawing technology conferred little advantage in mastering the Pilkington float glass process.

Other discontinuous innovations are *competence-enhancing*. These breakthroughs push forward the state-of-the-art by an order of magnitude, but build on existing knowhow instead of obsolescing it. Thus the turbofan jet engine is a competence-enhancing product innovation. It markedly improved engine performance, but built on existing knowhow instead of overturning it. The introduction of process control in cement kilns was a competence-enhancing process innovation. Computerization made possible enormous kilns, allowing cement manufacturers to employ their existing cement-making knowhow to make more and better cement than any human operator could produce.

Both product and process innovations may either enhance or destroy existing competences. Yet there is a fundamental difference between product and process innovations. Product innovations normally affect more links in the value chain than do process innovations. The customer must be made aware of new products; often, he is not aware of process innovations *per se*. New products often require distribution channels and suppliers different from those which serviced older products. Process innovations usually make the product better and cheaper without necessarily disrupting upstream and downstream linkages. Thus, a key factor is not only whether the core technical knowhow of an industry is disrupted by an innovation, but whether links in the value chain are overturned or reinforced by the new technology.

Characterizing the Technology Cycle

Discontinuities are generally uncommon, and their frequency varies greatly by industry. Nonetheless, they characterize both young and mature industries. We tracked 24 years of minicomputer data, over 100 years of cement industry history, and nearly 200 years of glass industry history and located only 17 discontinuities. The minicomputer industry passed through three discontinuities in a quarter-century, while the cement and glass industry experienced 50-year periods of incremental change. However, *every* industry we studied experienced at least one discontinuity since 1960, and the "mature" cement industry witnessed two.

More often than not, the pioneers of discontinuities are competitors you already know, not newcomers to the industry.

A *single* dominant design *always* emerged following a discontinuity, except in two situations. When one discontinuity follows another very rapidly (within 3–4 years), a dominant design may not have time to emerge before the second new technology displaces the first. When several producers each patent their own proprietary process and refuse to license to others, a dominant design may not emerge. Otherwise, in every case a single product or process architecture accounted for over 50 percent of new installations. Ultimately one standard prevails; we did not observe cases where two standards coexisted or where the position of dominance rotated among several competing designs.

The original discontinuous innovation *never* became a standard. Some improved version of the initial breakthrough became the basis of a dominant design in every case. Furthermore, more often than not dominant designs lagged behind the state-of-the-art at the time they were introduced. The winner of the design competition is seldom at the industry's performance frontier; typically, the industry pushes the state-of-the-art forward during the era of ferment, then standardizes on a design that is *behind* the leading edge of the technology.

The length of the era of ferment (the lag from introduction of the new technology to establishment of a dominant design with 50 percent of the market) depends on whether the discontinuity enhances or destroys existing knowhow. It took longer for an industry to converge on a dominant design following a competence-destroying discontinuity than it took to converge on a dominant design following a competence-enhancing discontinuity. When existing knowhow is reinforced, the industry arrives at a standard relatively rapidly; when it is overturned, it takes considerably longer for the design competition to culminate in a single technological guidepost. Furthermore, when a series of discontinuities enhance the same underlying competence, the length of the era of ferment grew shorter in each successive technological cycle, bolstering the argument that the more familiar the underlying knowhow, the easier it is to reach a standard.

DISCONTINUITIES

	PRODUCT	PROCESS
COMPETENCE DESTROYING	**NEWCOMER**	**VETERAN**
COMPETENCE ENHANCING	**VETERAN**	**VETERAN**

DOMINANT DESIGNS

	PRODUCT	PROCESS
COMPETENCE DESTROYING	**VETERAN**	**VETERAN**
COMPETENCE ENHANCING	**VETERAN**	**VETERAN**

Figure 3.—Veteran firms are more likely to pioneer each class of discontinuity and dominant design except the competence-destroying product innovation.

Pioneers of Discontinuities and Dominant Designs

A key competitive question is, when will a discontinuity overturn an industry—when will leaders become losers? Figure 3 summarizes our findings. Focusing on the first five firms to adopt an innovation, we observed that in general veterans—firms which competed in the industry before the discontinuity—are more likely to pioneer breakthrough innovations. This runs counter to the often-heard argument that revolutions usually come from outside an industry. It is often the case that the *initial* innovator is a newcomer to the industry, but when we look at the group of first-movers, we usually find that veterans predominate.

It is easy to understand why this is so when an innovation builds on existing knowhow. Firms which possess that knowhow—the veterans—are most likely to build on that expertise. It is also easy to understand why competence-destroying innovations are pioneered by newcomers. The new technology obsolesces what the veterans know, temporarily knocking down barriers to entry. Veterans are reluctant to adopt the new technology because it wipes out their considerable investments and forces them to change in fundamental ways. It is in this case that leaders are most likely to become losers. However, competence-destroying process innovations are typically pioneered by veterans, despite the fact that they are obsolescing their own process knowhow. We argue that veterans still are able to exploit strengths upstream and downstream in the value chain following a process discontinuity; only their core technical knowhow is overturned. As a result, veterans are willing to write off investments in existing facilities and expertise to exploit the price/performance advantage of the new technology.

Finally, dominant designs are *always* pioneered by veterans, whether or not they build on or destroy competences. The revolutionary is seldom the standard-setter. Recall that dominant designs seldom are state-of-the-art, and that industry experience is needed to understand what the market needs in a standard.

Creative Destruction

Industries are characterized by waves of foundings and failures. A period when the failure rate is unusually high is often termed a "shakeout." The conventional wisdom is that overcapacity or downturns in demand cause shakeouts. By analyzing mortality rates, we found no relationship between changes in demand and failure rates. Instead, failure rates were remarkably higher during eras of ferment than in any other period. The inability to adapt to a new technical order seems to kill more firms than the inability to withstand a recession in the industry. Interestingly, only one American cement firm failed during the Great Depression; in contrast, dozens failed when confronted with the challenge of adapting to new kiln technology.

Implications for Managers

The model of technology cycles provided here is one step toward developing what Foster terms "a language and a facility for talking about and directing technology." It allows managers in different industries to organize their view of the industry's technical history, and to compare the effects of various types of innovations on the industry's structure. Beyond this, we draw four principal lessons for managers from this research.

1. Expect discontinuities. They do not happen frequently, but they do occur even in mature industries, and they are watershed events. When evaluating potential discontinuities on the horizon, consider whether they would enhance or destroy fundamental competences in your industry. Consider developing competences that survive technological revolutions, such as flexible manufacturing capability or strong distribution channels.

2. When a discontinuity appears, expect an era of ferment culminating in a single dominant design (with the two exceptions noted above). Expect several designs to compete; expect one to emerge as a winner. The dominant design will seldom be a state-of-the-art architecture; it is usually introduced by industry veterans, and the time it takes to reach a design depends on whether the discontinuity is competence-enhancing or competence-destroying.

3. Realize that technological revolutions may be introduced by an industry newcomer, but the group of firms that adopt it earliest typically includes a majority of veterans. Only in the case of competence-destroying product discontinuities do we observe a preponderance of newcomers in the pool of first-movers. It is worthwhile to monitor potential competitors from outside an industry, particularly when you suspect that a new product technology can obsolesce existing knowhow. But more often than not, the pioneers of discontinuities are competitors you already know, not newcomers to the industry.

How the Electric Auto Could Evolve

To see how the ideas developed in this research can help managers understand the probable evolution of a specific new technology, consider the predicted development of an electric automobile, a technology currently in its infancy:

- A commercial electric automobile will become feasible following a breakthrough innovation, either in the power of electric motors (e.g., via superconductivity) or in power generation/storage technology (e.g., solar cells or improved batteries).
- The initial electric automobile will be a crude design, which will be elaborated and altered by dozens of imitators (*unless* the innovation enjoys strong legal protection from the outset). The displacement of conventional automobiles by electric automobiles will follow a classic S-curve, whose takeoff will be greatly aided by one or two key sales (e.g., to government vehicle fleets or a major auto rental company). Rival versions of the initial breakthrough will compete for legitimacy and substantially improve the product's performance.
- From the many versions of the initial innovation, one will emerge as the industry standard architecture, *de facto* or by regulation/agreement. This "dominant design" will account for over 50 percent of new electric automobile sales following its establishment.
- Following the establishment of the dominant design, the competitive focus of this product class will shift from performance improvement via significant architectural variations to cost reduction, market segmentation, and development/elaboration of the infrastructure that supports electric automobiles. Improvements will be incremental, and virtually all successful models will incorporate the key features of the dominant design. This regime of continuous improvement will continue until another discontinuity overthrows this generation of electric automobiles.
- If the discontinuity which paves the way for growth in this product class is a *process* discontinuity (e.g., superconducting power transmission), one should expect incumbent auto manufacturers and entrants from closely related fields (e.g., truck manufacture) to pioneer the new technology. The same would apply if the discontinuity is a component easily retrofitted to existing automobiles (e.g., a breakthrough battery). *Only* if the discontinuity involves a fundamental redefinition of automobile design (e.g., new concepts in motors, the body, power train, etc.) would we expect the process of "creative destruction" to replace today's vehicle makers with a new generation of companies spawned by the new technology.—**P.A. and M.T.**

4. Consider the implications of the finding that technological change, not downturns in demand, is associated with shakeouts. Top management always pays attention to industry recessions and is willing to make painful cost-cutting moves when demand drops. Yet it is not this form of competition that threatens the very survival of the firm and its rivals. Maintaining the organization's ability to navigate the rapids of creative destruction brought on by technological discontinuities is the key to fulfilling management's first duty to shareholders—preserving their capital by ensuring the continuance of the enterprise. The ability to direct the firm's marketing and financial operations helps top managers improve a firm's profitability. The ability to direct process and product innovation affects not only profitability but the viability of the firm itself in a world of technological upheaval.

Firms that competed in the industry before the discontinuity are more likely to pioneer breakthrough innovations.

Bibliography

Abernathy, William. 1978. *The Productivity Dilemma.* Baltimore: Johns Hopkins University Press.

Abernathy, William and Clark, Kim. 1985. "Innovation: mapping the winds of creative destruction." *Research Policy,* 14:3–22.

Abernathy, William and Utterback, James. 1978. "Patterns of industrial innovation." *Technology Review,* 2:40–47.

Abernathy, William; Clark, Kim; and Kantrow, Alan. 1983. *Industrial Renaissance.* New York: Basic Books.

Anderson, Philip. 1988. *On the Nature of Technological Progress and Industrial Dynamics.* Unpublished Ph.d. dissertation, Columbia University.

Bright, James. 1964. *Research, Development and Technological Innovation.* Homewood, Illinois: Richard D. Irwin.

Clark, Kim. 1983. "Competition, technical diversity, and radical innovation in the U.S. auto industry." In Robert Rosenbloom (Ed.), *Research on Technological Innovation, Management, and Policy:* 103–149. Greenwich, CT: JAI Press.

Fisher, J. and R. Pry. 1971. "A simple substitution model of technological change." *Technological Forecasting and Social Change,* 3:75–88.

Foster, Richard. 1986. *Innovation: the Attacker's Advantage.* New York: Summit Books.

Sahal, Devendra. 1981. *Patterns of Technological Innovation.* Reading, MA: Addison-Wesley.

Schumpeter, Josef. 1942. *Capitalism, Socialism and Democracy.* New York: Harper & Brothers.

Strassman, Paul. 1956. *Risk and Technological Innovation.* Ithaca, NY: Cornell University Press.

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