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Radical Innovation

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Abstract

This paper draws together case studies of radical innovation and academic research, to consider the relationship between the behaviors and strategies of firms with respect to technological innovation and long-term survival. Central to this discussion are the technological discontinuities created by innovation, and their impacts on the competencies that sustain established firms. Some of these discontinuities are shown to be compatible with a firm's existing capabilities, while others fly in the face of existing strengths, requiring new skills and methods that established firms are either incapable or unwilling to master. A broader analysis of the cases is provided to determine the sources of discontinuities in product and process industries. In brief, established, dominant firms are more attracted to incremental innovations than to radical innovations.

Innovation as a Game of Chutes and Ladders

There are rare moments in technology when the next 5, 10 or 15 years begin to crystallize; this is one of those moments.

Glen Zorpette, "Supercomputers," IEEE Spectrum, September 1992.

In the children's game of chutes and ladders one moves ahead in painstaking steps, turn after turn, in much the way that incremental improvement inches technology forward. Ralph Gomory and Roland Schmitt make the point that most products sold today were here in slightly inferior form last year, and most competition is between variants of the same product. Occasionally a player is lucky enough to land at the bottom of a ladder which allows him to quickly climb up to a higher level of the game's twisting path. Gomory and Schmitt liken this to the creation of a new idea leading to the potential for rapid development. The unlucky player can also land at the top of a slide or chute, which whisks him to a lower level, as is the case for the firm which chooses to coast in the face of rapidly changing technology. The generality of technological competition is that most time is spent on the tortuous, gradually inclined path, and firms that can run only a little faster than others will pull far ahead given time. Gomory and Schmitt contend that:

It is this process of incremental improvement that, after the initial ladder style invention of the transistor has given us better computer memories every year. In the last 20 years the number of memory bits per chip has gone from one to one million. Incremental improvement also has given us jet engines with double the thrust per unit weight of two decades ago, plastics that can be used at temperatures twice as high as a decade ago, and incandescent light bulbs that are fifteen times as efficient as Edison's.[1]

Indeed, a considerable part of this book has been devoted to detailing the process of continuous innovation and improvement in a number of industries. But what of the chutes and ladders. Despite their rarity the player who encounters a break in the path will have his or her fortunes either rudely reversed or happily improved. What happens when the evolutionary trajectory is disrupted by new technologies or other forces?

One arena in which we can see this clash of technologies now is in the field of supercomputing, where there is a discontinuity in the making. Cray in the United States and NEC in Japan hold the lead in speed and in market shares in what are today the fastest computers produced, the so-called supercomputers based on four, eight or sixteen blindingly fast processors made from exotic materials often running at extremely cold temperatures. The development of such processors has been methodical, and constitutes the tortuous path for Cray and NEC. Other companies, however, led by Thinking Machines and by Intel Scientific Computers are rapidly climbing a ladder that threatens the traditional makers of supercomputers by interconnecting hundreds or thousands of microprocessor-based nodes to form what have been described as "massively parallel supercomputers" (MPSs), whose processing powers may reach levels 100 times those of today's best machines.[2] Massively parallel supercomputers have the great advantage that they can be created from standard processor technologies and run at normal temperatures.

The market for massively parallel supercomputers came from nowhere to $538 million in revenues in 1993, and is expected to leap to the $1.6-$2.7 billion range by 1997.[3] In so doing, massively parallel supercomputers are expected to peel away business that would otherwise go to the old line supercomputer makers, as well as the traditional mainframe makers, like IBM. As one would expect, given earlier cases, the leading firms in this new market are all new entrants.

Naturally, the computing establishment is not totally oblivious to this threat. IBM, whose mainframe business has been under attack on the high end by supercomputers, and on the low end by personal computers and workstations, is developing its own capabilities through its Power Parallel Systems unit. "This is the future--and IBM will ride it," is how the leader of that unit, Irving Wladawsky-Berger, described parallel machines to the New York Times in the fall of 1993.

Identifying the path to the future is one important requirement for survival and success when discontinuities surface. For established firms, getting off the path they are currently on is another, and more difficult challenge. The impulse for firms to continue on the path of cash generating technologies is powerful. IBM, for example, has to deal with the reality that an estimated $1 trillion dollars worth of mainframe software is up and running in the customer universe, and that thousands of its employees and thousands of shareholders benefit mightily from its current mainframe business, however diminished.[4] The extent to which resources are diverted into parallel machine development--indeed, the very success of the new technology--threatens many of these interests.

As we will see shortly in the case of Digital Equipment Corporation, established firms are apt to approach discontinuities and conflicting corporate interests with compromises. In the case of IBM, the same article that quoted its parallel computing executive also described a forthcoming machine--the 390 Parallel--as a traditional mainframe computer with a parallel processing turbocharger. Bridging a technological discontinuity by having one foot in the past and the other in the future may be a viable solution in the short run, but the potential success of hybrid strategies is diluted from the outset compared to rivals with a single focus.

The Tortoise and the Hare

Gomory and Schmitt contend that if a firm moves only slightly faster than its rivals in incremental improvement it will appear to have newer products with newer technologies, even though all the firms are drawing from the same level of technical knowledge. This is surely true when all are pursuing improvement of the same basic design or production process. However, Fernando Suárez and the author have shown that the advent of a new technological ensemble, or ladder, is marked by a wave of new competitors entering the industry. To sustain success requires mastery of the infrequent discontinuities, as well as mastery of the constant competitive and customer demands for rapid incremental improvement. How can companies sustain success when they know that the technologies underlying their products and markets will change periodically?[5]

Even the largest and strongest firms find this to be a struggle. IBM for example, according to David Kirkpatrick, has been from three to eleven years behind the curve in each case of revolutionary change.[6] Digital led IBM by 11 years in introducing the minicomputer, Apple led by four years in introducing the personal computer, Apollo was five years ahead in introducing the engineering workstation, Toshiba by five years with the PC-compatible laptop, and Sun Microsystems led by three years with its Sun 4 RISC workstation. IBM's late introduction of RISC is particularly troubling in that it was clearly years ahead of others in originating and advancing RISC technology in its corporate laboratory. And though IBM is now seriously moving to enter the market for massively parallel supercomputers its newer rivals have again stolen the march by five or more years. Evidently it is the very success and dominance of large firms that leaves them vulnerable to new entrants to their business. Indeed former chairman John Akers proposed that splitting IBM up into more manageable pieces may be the right course to reduce complacency and to increase the market responsiveness of each part.

Evidence and Advice

We contended earlier that new technologies have made industrial giants out of once small, upstart firms, invigorated those older ones that were receptive to change, and swept away those that were not. This paper draws the threads of both examples and observations more tightly together to reexamine the question raised at the outset: Can we better understand which firms will be able to ride the crest of a wave of change while others are left gasping in the undertow? Are there managerial principles for staying on top, or is long-term success and survival a matter of pure luck?

At the outset of this book we noted that Schumpeter considered innovation both the creator and destroyer of corporations and entire industries. Cristiano Antonelli, Pascal Petit and Gabriel Tahar note that, "in his early works Schumpeter (1912) insisted on the role of entrepreneurs in seizing discontinuous opportunities to innovate. Innovations were taken in a broad sense of new 'combinations' of producers and means of production, which includes new products, new methods of production, opening up of new markets, utilization of new raw materials, or even the reorganization of a sector of the economy." They continue, "this initial approach stressed the discontinuities of the innovation process."[7] In later years (1942) Schumpeter began to place greater stress on the role of larger enterprises in innovation, seeming to believe that as scientific knowledge accumulated there was a threshold investment in R & D below which a firm could not be an effective player. The writer has always been troubled by this conflict in Schumpeter's views. The present analysis suggests that the former hypothesis is true for areas of emerging product technology and firms involved in product innovation, especially for assembled products (that is for discontinuous and fluid phases), while the latter hypothesis might well hold for process innovation and for many nonassembled products, and for firms producing standard products and large systems (the specific phase).

Following Schumpeter's path breaking, work researchers in the main focused on the concepts he laid out, and studied invention (ideas or concepts for new products and processes), innovation (reduction of an idea to first use or sale) and diffusion of technologies (their widespread use in the market). Indeed this was the framework used by Myers and Marquis in their influential study[8], by the author[9] and by Project Sappho[10], the first extensive study of matched successful and unsuccessful innovations. Cooper and Schendel were the first to turn the lens in the opposite direction in a provocative analysis of major technological innovations from the viewpoint of firms in established industries threatened by innovation. They note that

> ...a typical sequence of events involving the traditional firm's responses to a technological threat begins with the origination of a technological innovation *outside the industry*, often pioneered by a new firm. Initially crude and expensive, it expands through successive sub-markets, with overall growth following an S-shaped curve. Sales of the old technology may continue to expand for a few years, but then usually decline, the new technology passing the old in sales within five to fourteen years of its introduction. [Emphasis added].[11]

Not only do the sales of the established technology decline, but the traditional leaders in the industry also lose position. Why is this so? Clearly the traditional firms are financially strong, and they have sophisticated market knowledge and distribution channels as well. Richard Foster and I were inspired by the questions posed by Cooper and Schendel's work and by cases and observations posed by James R. Bright and began to work independently to examine them. Foster has based his analysis on the theory of technological limits, while Linsu Kim and I were more concerned with firms' behavior and competitive responses. We came up with remarkably similar results. The most obvious explanation for the demise of established leaders in an industry would be that they have skills in the old product or process technology, while the entrepreneurial firms have a base in the new. Perhaps the most surprising observation from examining many cases of discontinuous change is that differences in technological resources do not much discriminate between invading and traditional firms in an industry either. Most threatened firms do participate in the new technology and often have pre-eminent positions in it. The basic problem seems to be that they continue to make their heaviest commitments to the old, which reaches the zenith of its development only after it is mortally threatened. Cooper and Schendel put it as follows:

> The traditional firms fight back in two ways. The old technology is improved and major commitments are made to develop products using the new technology. Although competitive positions are usually maintained in the old technology, the new field proves to be difficult. In addition to the major traditional competitors (who are also fighting for market share in the new field), a host of new competitors must be confronted. Despite substantial commitments, the traditional firm is usually not successful in building a long-run competitive position in the new technology. Unless other divisions or successful diversifications take up the slack, the firm may never again enjoy its former success.[12]

Cooper and Schendel conclude that a dual strategy is simply not a viable way to gain a leading position in the new. Threatened firms continued to make added commitments to developing old products even after their sales had begun to rapidly decline. Their explanation for this difficulty is that, "decisions about allocating resources to old and new technologies within the organization are loaded with implications for the decision makers; not only are old product lines threatened, but also old skills and positions of influence."[13]

If one were to bet purely on the basis of technological resources that a firm would master a discontinuity, then one would probably bet on an entrepreneurial firm with a sophisticated technology base and a high degree of development spending (as a proportion of sales) in an industry characterized by rapid generational changes, each of which represents a relatively small step from the past. Surely such a firm would find it difficult to become entrenched. Henderson and Clark have recently studied just such an extreme case. They conducted a comprehensive review of the semiconductor photo-lithographic alignment equipment industry. Every firm in the industry was studied through five generations of architecturally different product technologies, meaning that components were integrated into a system in different ways. Astonishingly, no firm which led in one generation of product figured prominently in the next! Henderson and Clark conclude that even relatively minor shifts that lead to changes in systems relationships can have disastrous effects on industry incumbents. Their explanation is that such innovations "destroy the usefulness of the architectural knowledge of established firms, and since architectural knowledge tends to become embedded in the structure and information-processing procedures of established organizations, this destruction is difficult for firms to recognize and hard to correct."[14]

The Survival of Some Threatened Firms

Once the old technology begins to modernize itself in response to the invasion by the new, the emphasis in competition shifts to product change and away from cost and quality, while at the same time, prices may drop with extraordinary rapidity, and many new options and performance dimensions may become available to users. The total market may even expand as a direct consequence of the invading innovation. However, this only postpones the inevitable abrupt decline of the established technology and lends false strength to arguments against withdrawal from the old and rapid investment in the new.

In some product lines, the last few firms in the established technology can be highly successful and profitable and even highly innovative. There will probably always be a demand for fine mechanical watches for example, and perhaps the few firms that survive the present shakeout in the industry will be highly profitable and stable companies. And the few firms which remain manufacturing vacuum tubes probably supply a highly specialized and profitable market for high performance designs, research and other specialized applications.[15]

While each of the studies reviewed, as well as my own work with Kim, describe the dynamics of discontinuous change, the advice given to management is disappointing. Cooper and Schendel believe that their work illustrates some of the approaches and pitfalls in discontinuous change that management should consider. Their message accurately portrays the low probability of success in either defending the old position or successfully entering the new, and seems to recommend diversification as a singularly viable option. Foster speaks to the entrepreneurial attacker with excellent advice on ways to take advantage of established firms which tenaciously want to believe that the looming threat of an innovation is either unimportant or that it will go away. Anderson and Tushman argue that, "the closing of an industry standard is an inherently political and organizational phenomenon constrained by technical possibilities," and that, "the passage of an industry from ferment to order is not an engineering issue as much as a sociological one."[16] Henderson and Clark conclude that their work underscores the need to deepen our understanding of the distinction between innovation that enhances and innovation that destroys competence within the firm, and point out that systems changes can subtly do both, sometimes misleading the firm to believe that because it understands the components it must therefore understand the system they form as well. They suggest that an organization that can learn quickly and effectively about components may not be able at all to fathom systems relationships. Christensen counsels firms not to be so attentive to large and familiar customers. The demands of these customers can lead a firm down the garden path to spending royally on marginal improvements for older concepts, all the while ignoring newer customers in small but growing markets that support new concepts. This advice is especially valuable in view of the current doctrine to "listen to the customer." But which customer should firms listen to? Linsu Kim and I concluded that discontinuities which break market and manufacturing process linkages will be more threatening to the firm than those which break either one or the other. We suggested that discontinuous process changes will be more likely to be introduced by established firms producing homogeneous products like glass than assembled products like televisions. Finally, we suggested, as did Cooper and Schendel, that discontinuities which expand the market are seemingly less threatening to established firms than are those which simply create substitute products.

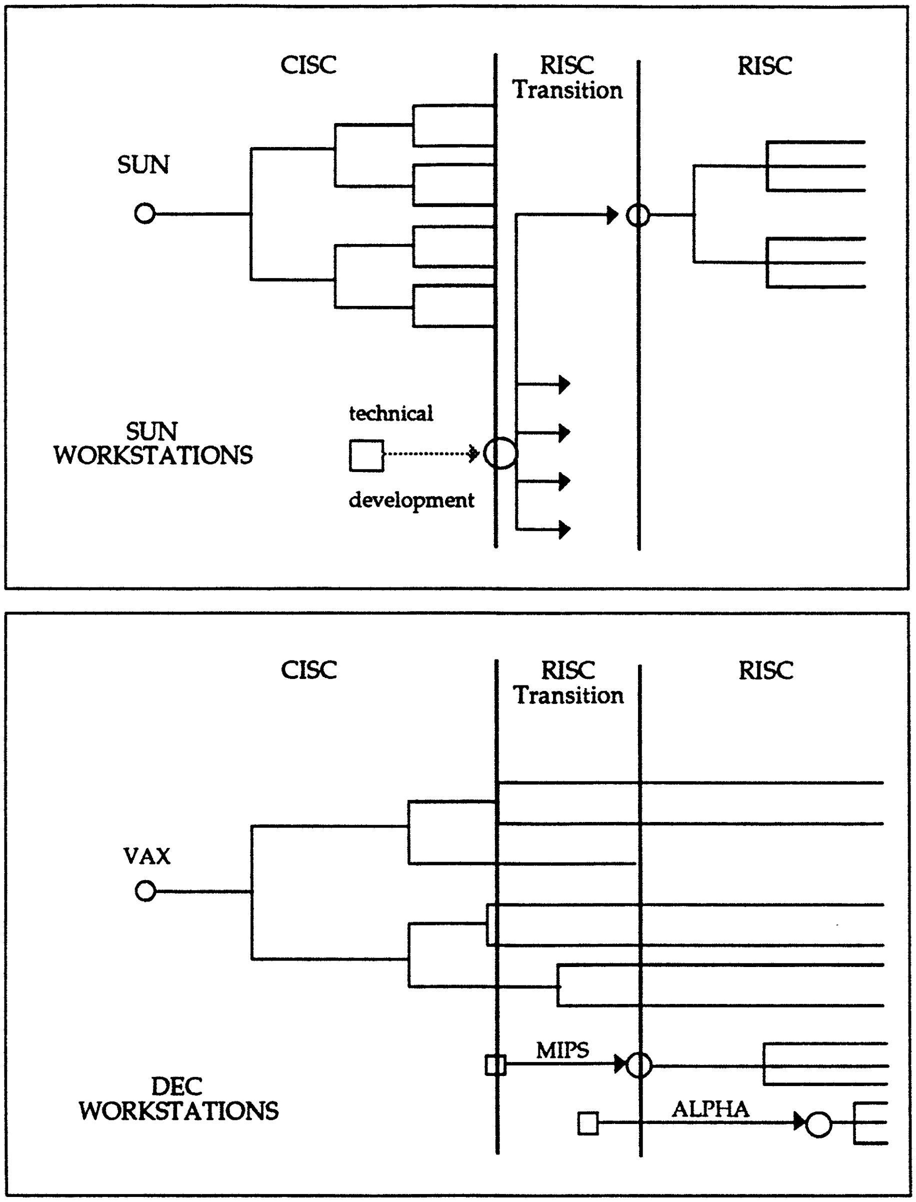
None of these studies, unfortunately, successfully address the key problem: how established firms can renew their core technologies when they become obsolete, thereby avoiding retrenchment and failure. (This question is the more compelling in a year when retrenchment for firms like IBM, DEC, Kodak and General Motors means quarterly reductions of tens of thousands of employees). Each analysis is limited in much the way that the views of the fabled eight blind men and the elephant were limited. Each has a part of the truth, but that part alone is misleading. To more fully develop our understanding we will combine the data from each of the earlier studies mentioned, as well as those from a number of single but intensive case studies of discontinuous change, and use these combined data to construct a three factor model to further understand the impact of such changes. We will show that under some circumstances leaders of well established firms should certainly plunge forward to invest in a radically different technology, while in other circumstances they clearly should not, and certainly not with a dual strategy.

A Case of Focused versus Dual Strategy

As earlier chapters have made clear, discontinuities caused by innovation more often than not create chasms that few firms can bridge. A few find their ways across, but most fall into the abyss. Susan Walsh Sanderson of Rensselaer Polytechnic Institute has provided a vivid contemporary example of two leading firms in the same industry that ran up against a technological discontinuity, describing how one firm effectively bridged to a new product architecture, while the other continued to struggle. In "Managing Generational Change: Product Families Approach to Design,"[17] Sanderson used the shift from CISC (complex instruction set) to RISC (reduced instruction set) architectures in computer workstations to show how Sun Microsystems made a clean break from its established system to launch a new and successful generation of workstations. (RISC architectures are simpler and faster than the now common CISC architecture.) Digital Equipment Corporation (DEC), burdened by the success of its popular VAX system, "dragged its heals in making an investment in RISC and then did so in a half-hearted way."

Figure 9-1 represents the product family strategies of the two firms. In the case of Sun, continued extension of its CISC-based products effectively ends at the point where RISC technology creates a discontinuity. In 1989 the firm developed a new family of workstations with the RISC architecture, based upon a microprocessor of its own design: the "Sparc" chip. By 1991 Sun had made a clean break with its older generation workstations, devoting all of its energies to the family of products that emerged from the new architecture.

Figure 9-1 Sun and DEC: Generational Product Strategies



Source: Sanderson, see footnote 17 With permission.

DEC, with its wide range of minicomputers and workstations, according to Sanderson, had a long-standing strategy of supporting compatibility among its own products and those of major competitors. Its large established base of customers and installed equipment presented an obstacle to DEC's making the transition to the

RISC architecture, where continuity and compatibility would be threatened. It waded into the RISC technology slowly, all the while maintaining its commitment to its existing family of VAXstation products. A new generation of workstation based upon a proprietary "Alpha" chip was planned for the future.

The bottom of Figure 9-1 describes DEC's workstation family and development strategy. Here, the CISC-era VAX family is shown being carried through into the RISC-era, while its own RISC-based machines (using MIPS Corporation chips) provide a smaller part of its workstation effort. The new Alpha machines are shown proceeding from development to market to product family somewhat later in the game. As Sanderson relates, "DEC had built its empire on the VAX architecture and could not find a painless migration either for itself or its customer. It waited too long to make the necessary transition and almost lost the company (author's emphasis)."

While it may be that DEC's Alpha chip will lay the groundwork for future success and growth, many observers believe that the company will bear greater than necessary dislocations in moving forward due to its continuing commitment to multiple, but parallel product architectures. The extent to which Sun Microsystems "bet the company" in this episode, or the extent to which its strategy of abandoning the older generation of workstations burdened future cash flows, is not made clear in Sanderson's discussion. We can surmise, however, that the stakes were considerable. By 1991, the year in which the firm made its break with its CISC-based architecture, Sun was already a multi-billion company with 38 percent of the the workstation market. Workstations were, in fact, its only real business. Thus, Sun's decision to move entirely to RISC-based architecture was more survival-threatening than was DEC's decision to move with all deliberate caution. DEC was a much smaller player in the total workstation market and had plenty of other business to sustain it. The CISC to RISC transition going on in computers seems a compelling example of the reasons not to play a dual strategy of sustaining both the new and the retiring product at a time of radical change.

Continuities and Discontinuities

The evolutionary model outlined by Abernathy and Utterback described continuous change in products and processes as a transition from an earlier "fluid" state to one that is highly "specific" and rigid.[18] As continuous change proceeds, technological diversity gives way to standardization. These evolutionary periods do not continue indefinitely, but are often interrupted by a new cycle of creativity and discontinuous change. By discontinuous change or radical innovation, we mean change that sweeps away much of a firm's existing investment in technical skills and knowledge, designs, production technique, plant and equipment.

Earlier chapters of this book have provided abundant examples of powerful discontinuities, in which either a change in product or the process architecture caused important dislocation at the level of the firm and throughout entire industries. Figure 9-1 presents a summary of these discontinuities.

Figure 9-2. Product and Process Discontinuities

Industry	Discontinuities
Typewriters	manual to electric; to dedicated word processors; to personal computers
Lighting	oil lamps to gas; to incandescent lamps; to fluorescent lamps
Plate glass making	crown glass; to cast glass through many changes in process architecture; to float process glass
Ice & Refrigeration	harvested natural ice; to mechanically made ice; to refrigeration; to asceptic packaging
Imaging	daguerreotype; to tintype; to wet plate photography; to dry plate; to roll film; to electronic imaging; to digital electronic imaging

The typewriter. Discontinuities were observed between the periods of the manual typewriter, electrics, dedicated word processors, and personal computers. Of the large manual typewriter firms of the early twentieth century, none were successful in jumping onto the bandwagon of electric typewriters; it was IBM, an outsider, that developed both the product and its market. Likewise, the move to word processors and then personal computers caused equal dislocation, virtually none of the original typewriter companies, excluding IBM, having made the leap. Indeed, virtually none survive in their past forms.

Lighting. The change from lighting with candles to the modern system of electrical illumination has all taken place (in most of the western world) within a period of 150 years. Oil lamps displaced candles and were in turn displaced by gas in most urban areas. Electric lamps of the Edison design displaced gas, and fluorescent lamps have displaced these in many instances. Each wave of change has brought a different champion to the fore; and,.with the exception of the non-leadership position of Edison's successor firm (GE) in fluorescents, no firms have successfully bridged the discontinuities.

Plate glass. The generations of discontinuous and incremental change in this industry have virtually eliminated all but a handful of highly capitalized, high-volume producers. There would be even fewer firms in this important industry today had the Pilkington Company decided to protect its patents on the Float glass process and simply run over its competition. Instead, it chose to license that breakthrough technology to other glass firms, which allowed them to survive. With almost all the glass in the developed world being made under this process, those that did not switch to it were largely eliminated.

Ice and Refrigeration. No doubt a few local hold-outs in places like Maine and northern Minnesota continue to harvest ice for commercial sale; but the other firms are gone. So too are most of the firms that displaced the Ice Kings with mechanically manufactured ice. They in turn fell prey to the innovation of electro-mechanical refrigeration; the broad market for ice produced by nature or by machines disappeared almost forty years ago. Here again, the agents of change were not the leaders of the established technology.

Imaging. The transition from daguerreotype to modern film photography, and the emerging technology of electronic imaging, was punctuated by many discontinuities: tintype to wet and then dry-coated glass plates, and then sheet celluoid and roll film. Each transition was inspired by a different party, rarely the market leader, and each transition led to the period in which old producers were replaced by new ones.

In addition to these cases we will cover those analyzed by Cooper and Schendel: steam to diesel locomotives, vacuum tubes to transistors, fountain to ball point pens, safety razors to electric razors, fossil fuel boilers to nuclear boilers, propellers to jet engines, and natural to synthetic leather. Also, cases from the cement industry and minicomputer industry contained in Anderson and Tushman, and cases from Utterback and Kim; mechanical to electronic calculators, woven to tufted carpet, transistor to integrated circuit, open to closed body cars, rayon to nylon tire cord, air cooled to hydrogen cooled generators, open hearth to basic oxygen furnaces and other examples from steel making, continuous drawing of copper wire, synthetic gems and small scale production of industrial gases. To add to the case so completely analyzed by Henderson and Clark we include a number of other intensive single product cases: radial for bias ply tires, oriented strand board for plywood, optical fibers for copper wire, and massively parallel for von Neumann supercomputers.

Framework.

The combined sample just described consists of 46 discontinuous innovations, of which 26 are product discontinuities and 20 are process discontinuities. Nearly one-quarter of the 46 innovations come from within firms which are established competitors (12 of 46), while the remainder--a large majority (27 of 46 --come from firms entering the industry. (The sources of the other 7 are undefined for the most part because no industry existed prior to the innovation in question). The entire sample is shown in detail in Figures 9-2 and below.

The purpose here is simply to attempt to put the differing blind mens' views of the elephant together in order to get a more comprehensive and accurate picture of the whole. Doing so will provide a remarkably accurate discrimination between the cases which were mastered by traditional firms as opposed to those which came from beyond their circle of known competitors. To put this mosaic together we will first look at each of three factors highlighted in the prior studies separately, and then endeavor to examine them jointly. These factors are:

- does the discontinuity pertain to an assembled or a nonassembled product;
- is it simply a substitution or does it create a broadened market; and
- is it competence-enhancing or competence-destroying for the established firms in the industry?

Our hypothesis is that each of the three factors is important, and that they will operate more powerfully jointly than separately.

Assembled vs. Nonassembled, or Homogeneous Products

Linsu Kim and I argued in 1986 that discontinuous changes in processes pertains primarily to industries producing homogeneous products. In fact this is true for the entire 20 process discontinuities in the combined sample. We claimed that such discontinuities would usually be introduced by established firms, in sharp distinction to the general arguments posed above, often by marginal firms seeking to expand market share, or by dominant firms under severe cost, supply or regulatory pressure. We further concluded that occasionally such changes might be introduced by equipment suppliers, who may also enter production in their own right. We reasoned in part, based on von Hippel's work and earlier findings from Project Sappho, that the most demanding users of process equipment and those with the most subtle information about demands would be the users of the manufacturing equipment themselves. It was our contention that discontinuous changes in processes will primarily emphasize real or potential cost reduction, improved product quality, and wider availability, and require movement toward more highly integrated and continuous production processes.

Figures 9-2 and 9-3 show that discontinuous innovations in assembled products almost always come from outside the industry (15 of 21 cases, with 3 from internal sources and 3 inconclusive). Discontinuous innovations in nonassembled products often come from inside the industry (9 of 25 cases, with 12 from external sources and 4 inconclusive), but more often from outside. Fully three-quarters of all the cases coming from within the established industry fell into the homogeneous product category.[19]

Is a Discontinuity a Substitute or Does It Create a Broadened Market?

A discontinuous change may drastically increase the aggregate demand for the products of an industry. The replacement of the vacuum tube by the transistor, and later the integrated circuit, has increased the sales of the electronics industry from several billions of dollars to hundreds of billions. The replacement of piston aircraft engines by turbojets has correspondingly dramatically reduced the costs and increased the seat miles flown by commercial aircraft. The advent of the electronic calculator has made such equipment commonplace rather than something rarely encountered. The advent of Eastman's Kodak camera and roll film system transformed photography from a small professional market to the large and now familiar amateur market. Replacement of carbon filament incandescent lamps by those based on metal filaments multiplied the demand for incandescent lamps from twenty million to hundreds of millions per year in the United States alone. The invasion of machine made ice tripled the demand for harvested ice from 5 million tons per year to 15 million tons per year. Each revolution in glass making led to a corresponding sharp increase in aggregate demand for flat glass, and the advent of on-site production of oxygen led to more than a doubling in the demand for oxygen.

Reasoning from the general arguments given in Utterback and Suárez, one would expect that innovations which broaden the market would create room for new firms to start, and that innovation-inspired substitutions would cause established firms to hang on all the more tenaciously making it extremely difficult for an outsider to gain a foothold and the cash flow needed to expand and become a player in the industry.[20] Figures 9-3 and 9-4 show that discontinuous innovations that expand markets will almost always come from outside the industry (15 of 18 cases, with 1 from inside and 2 inconclusive). Discontinuous innovations that substitute for established products and processes often come from inside the industry (11 of 28 cases, with 12 from outside and 5 inconclusive). This is in line with our explanation. Eleven of the twelve internally created discontinuities were substitutions, but twelve of the discontinuities that were substitutes also come from outside sources for this combined sample.[21]

In summary, some discontinuities broaden a market, allowing new firms to enter and survive. Established firms are more likely to fail than succeed, but may do succeed. New and established firms have roughly equal chances. Examples include the transistor, personal computer, and massively parallel supercomputer cases discussed earlier. Some discontinuities do not broaden a market or create a new niche. In such a situation new firms experience tough sledding. Fewer, and larger firms may survive. Established firms are likely to enter successfully. Established firms also have greater survival chances in these instances than do new firms. Examples include the electric typewriter and metal filament lamp cases discussed in earlier chapters.

Some discontinuities create a wholly new market niche, encouraging the many new entrants. Here, established firms are unlikely to enter successfully and new firms have better survival odds. Examples include the typewriter, automobile, television and television tube cases discussed in earlier chapters. Recall that "new" has a specific meaning: Corning in optical fibers; Remington in typewriters; General Motors in locomotives; as well as new entrants such as Genentec in biotechnology; Digital Equipment in minicomputers, and so forth.

Is a Discontinuity Competence-Enhancing or Competence-Destroying?

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

"A competence-enhancing discontinuity," Tushman and Anderson wrote, "builds on know-how embodied in the technology that it replaces. For example, the turbofan advance in jet engines built on prior jet competence, and the series of breakthrough advancements in mechanical watch escapements built on prior mechanical competence. Similarly, the Edison cement kiln allowed cement makers to employ their existing rotary kiln knowledge to make much greater quantities of cement. Later retrofitting of process controls to cement kilns again allowed manufacturers to build on accumulated know-how while dramatically accelerating production through minute control of the process."[22]

Figures 9-3 and 9-4 show that discontinuous innovations that destroy established core competences (in technology) almost always come from outside the industry (23 of 29 cases, with 4 from inside and 2 inconclusive). Discontinuous innovations that enhance established core competences (in technology) often come from inside the industry (10 of 17 cases, with 4 from inside and 3 inconclusive). [23]

Figure 9-3. Competence Destroying Product and Process Discontinuities[24]

Assembled/ Substitutes	**Assembled/ Market Broadening**
Photo-lithographic Aligners (A)	Solid State Minicomputers (N)
Radial Tires (A)	Integrated Circuits Minis(A)
Diesel Locomotive (A)	Transistor (A)
Ball Point Pen (A)	Electronic Calculator (A)
Jet Aircraft Engine (A)	Tufted Carpet (A)
Refrigerators (A)	Massively Parallel Super-computers (A)
Incandescent Lamps (A)	
All Steel Automobile (A)	
Nonassembled/ Substitutes	**Nonassembled/ Broadening**
Suspended Pre-heating (D)	Rotary Kiln (A)
Glass Drawing (D)	Container Machine (N)
Continuous Forming (D)	Owens Process (A)
Float Glass Process (D)	Vinyl (E)
Basic Oxygen Steel (A)	Celluloid film (A)
Direct Reduction of Iron (A)	Manufactured Ice (A)
Optical Fibers (A)	Synthetic Gems (A)
	Small Liquid Oxygen Plants (A)

(A) an innovation originated predominantly from a new entrant or attacker, (D) an innovation originated predominantly from an established firm, or defender, (N) the origin of the innovation has not been classified, mainly cases in which no prior industry existed.

Figure 9-4. Competence Enhancing Product and Process Discontinuities[25]

Assembled/ Substitutes	**Assembled/ Market Broadening**
Nuclear Steam Supply (A) Air-cooled Engines (D) Nylon Tire Cord (N) Hydrogen Cooled Generator (D) Fluorescent Lamps (N)	Semiconductor Memory (D) Electric Typewriter (A)
Nonassembled/ Substitutes	**Nonassembled/ Broadening**
Computerized Kiln (D) Edison Long Kiln (D) Machine Cylinder Glass (D) Gob Fed Bottle Machine (D) Double Gob Machine (D) Continuous Casting (D) Continuous Drawn Copper (D) Oriented Strand Board (D)	Integrated Circuits (A) Continuous Vertical Kiln (A)

(A) an innovation originated predominantly from a new entrant or attacker, (D) an innovation originated predominantly from an established firm, or defender, (N) the origin of the innovation has not been classified, mainly cases in which no prior industry existed.

All Three Factors Taken Together

Discontinuous innovations that would be most disruptive based on the arguments above, those in assembled products that expand established markets and that destroy established core competences virtually always come from outside the industry (5 of 6 cases, with 1 inconclusive). These cases have been given a score of 3 in Figure 9-5 below. Discontinuous innovations that would be least disruptive based on the arguments above, those in nonassembled products that substitute for established products and that enhance established core competences (in technology) virtually always come from inside the industry (7 of 8 cases, with 1 inconclusive). These cases have been given a score of 0 in Figure 9-5 below. Intermediate cases, for example,ones that expand established markets and/or that destroy established core competences will virtually always come from outside the industry. (16 of 18 cases, with 1 from inside and 1 inconclusive). Cases in which just one of the three factors discussed is present in its most disruptive form have been scored 1. Such cases about equally come from inside or outside the industry (6 of 14 cases from new entrants, with 6 from inside and 2 inconclusive).

Using the eight categories formed by the three dimensions it is striking to see that the cases contained in the extreme cells are classified perfectly. This would be hard to imagine happening with a larger and more representative sample.

Figure 9-5. Number of Cases for Three Variables Considered Together[26]

Score	Inside Source	Outside Source
Three factors positive	0	5
Two factors positive	1	16
One factor positive	6	6
All factors negative	7	0

Summary

Earlier work on technological discontinuities has concluded if not that practically all established firms fail to master radical innovation then at least that it is a highly random and unpredictable process. However, extracting the three factors highlighted in earlier work which attempted to discriminate between situations in which new entrants were advantaged and those in which established firms hold the cards may allow us to tell a slightly different story. While it is true that a large fraction of radical innovations are indeed introduced and taken up by competitors new to an industry, in about one-quarter of the cases studied existing competitors either introduced or were able to quickly imitate radical innovations and survive as major players in their markets. Thus, established firms need not always fail in this arena. More importantly, we may be able to see even in the rough analysis given above the conditions favorable to their success, so that they can analyze and act accordingly.

Clearly technology is not the key in and of itself. Market conditions are an equally powerful influence. And while technology and markets are important, their importance must be understood in conjunction with the human factors determining organizational competence or core capabilities. When core capabilities are aligned (as in the case of the replacement of plywood by oriented strand board) management can attempt to make a discontinuous change internally. When not, an alliance or outside venture is called for, or great effort must be invested to create appropriate human resources and cultural change before attempting the innovation.

Clay Christensen's work shows that established firms were the real leaders in introducing thin film disc drives, which displaced their own magnetic technologies. Most of the new entrants failed in this essentially evolutionary change.[27] Likewise IBM spent $300 million to develop the thin film head for its hard disc drives, while DEC spent $200 million. On the other hand new entrants were the leaders in introducing new architectures (in Henderson and Clarks' terms the same technological idea, but having components related in different ways). Established firms led the difficult but incremental improvement of components. New firms led with new architectures using established components. The leaders in incremental innovation were not able to keep that proprietary. Incremental innovation did not affect industry structure despite its high cost. New entrants with architectural change, despite its being fast and cheap, dethroned the leading companies in the Winchester disc drive industry.

Why are firms willing to pay hundreds of millions of dollars for incremental changes and not a few million dollars for a new frame size? Because the new frame size did not address the *needs of their established customers*. (Another kind of persistence of competence.) Smaller drives at first were much slower and more expensive, but they did enable a hard drive on the desk top. A good analogy is the car companies discouraging Goodyear, Firestone and others from introducing radial tires, because they did not want to change the design of the suspensions on their cars.[28] Similarly, IBM's problem is not that it does not listen to its customers carefully, but rather may be that it attends to a powerful set of customers dragging it along the wrong technical trajectory. Virtually all mainframe computers are sold to customers who already use mainframe computers, and who have large switching costs due to investments in software, procedures, and so on. Perhaps this is one of the critical clues to the failure of established firms. Clay Christensen finds very uniformly that the competitors firms monitor are the ones that are in the same technology and architecture. But the competitors that are most threatening will be those coming from the unexpected direction with a new architectural concept, such as massive parallelism in computation.

Ironically then following advice to be market driven in pursuing innovation, delighting one's customers through continuous improvement of products, and seeking out lead users may be both powerful concepts for success or a road to failure depending on circumstances. These are good ways for a new entrant to identify and specify a valuable direction for change. They are good lessons to follow in promoting evolutionary change in well understood product lines. But when applied to a discontinuity they may lead a strong firm into a dangerous trap. Similarly, ideas such as lean manufacturing (with regard to product and manufacturing competences) and mass customization (with regard to marketing and distribution competences) may be thought of as a way to build core competence and to be highly successful in differentiating well known products. These concepts too may lead to a dead end when radical change is in the wind.

The destructiveness of a change such as machine made ice is rather surprising. Product, market and distribution linkages were left entirely intact. Only the ice harvesters' manufacturing competences were severed, but this still seemed like a total revolution to them. By the same reasoning the electric refrigerator should have been, and was, much more competence destroying, laying waste to product, marketing and distribution competences as well as manufacturing. Now the customers could make their own ice for drinks on demand! The key question is not just whether an innovation is competence enhancing or destroying, but for whom? Goodyear and Firestone saw radial tires as cutting into the market for bias-ply tires, while Michelin saw them as expanding the market both in size and geography. Kodak may see electronic imaging as cutting into its market for chemical imaging and eroding high profit margins, while Canon and Sony may see the same innovation as expansive and as raising relatively lower margins. Being able to answer this question may give us a sharper understanding of firms' potential vulnerabilities and strategies.

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[1] Ralph Gomory and Roland W. Schmitt, "Science and Product," Science, Vol. 240, May 27, 1988, p 1131.

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[2] Glenn Zorpette, Issue Editor, "Teraflops Galore," Special Report: Supercomputers, IEEE Spectrum, September 1992, p. 27.

[3] Steven Lohr, "Well, Somebody's Got to Reinvent the I.B.M. Mainframe," The New York Times, September 12, 1993, p. 8.

[4] Ibid., p.8.

[5] We have shown that the frequency of these sorts of changes depends on the type of industry and the intensity of competition.

[6] David Kirkpatrick, "Breaking Up IBM," Fortune, July 27, 1992, p. 47.

[7] Cristiano Antonelli, Pascal Petit and Gabriel Tahar, The Economics of Industrial Modernization, (London: Academic Press, Harcourt Brace Jovanovich, 1992).

[8] Sumner Myers and Donald Marquis, Successful Industrial Innovations, (Washington, D.C.: The National Science Foundation (NSF 69-17), 1969).

[9] James M. Utterback, "The Process of Innovation: A Study of the Origination and Development of Ideas for New Scientific Instruments," IEEE Transactions on Engineering Management, Vol. EM-18, No. 4, November 1971, pp. 124-131.

[10] Roy Rothwell, C. Freeman, A. Horsley, V.T.P. Jervis, A.B. Robertson and J. Townsend, "SAPPHO Updated - Project SAPPHO Phase II," Research Policy, Vol. 3, No. 4, 1974, pp. 258-291.

[11] Arnold Cooper and Daniel Schendel. "Strategic Responses to Technological Threats," Business Horizons, Vol. 19, No. 1, February 1976, pp. 61-69.

[12] Ibid., p. 61.

[13] Ibid., pp. 68-69.

[14] Rebecca Henderson and Kim Clark. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," Administrative Science Quarterly, Vol. 35, No. 1, 1990, p. 9.

[15] James Utterback and Linsu Kim, "Invasion of a Stable Business by Radical Innovation," in Paul Kleindorfer (ed.), The Management of Productivity and Technology in Manufacturing (New York: Plenum Press, 1986), pp. 129-130.

16 Philip Anderson and Michael Tushman. "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change," Administrative Science Quarterly, Vol. 34, No. 4, December 1990, p. 627.

17 Susan Walsh Sanderson, "Product Families Approach to Design," Proceedings of the Design and Manufacturing Systems Conference, (Washington D.C.: National Science Foundation, January 19, 1993).

18 Abernathy, William J. and James M. Utterback, "Patterns of Innovation in Industry," Technology Review, Vol. 80, No. 7, 1978, pp. 40-47.

19 The probability that this strong a relationship would be found by chance alone is less than one in one-hundred. (Chi-square test, $p < .01$.)

20 Utterback, James M. and Fernando F. Suárez, "Innovation, Competition and Industry Structure," Research Policy, Vol. 22, No. 1, pp. 1-21.

21 The probability that this strong a relationship would be found by chance alone is less than one in one-hundred. (Chi-square test, $p < .01$.)

22 Anderson and Tushman, ibid, p. 609.

23 The probability that this strong a relationship would be found by chance alone is less than one in one-hundred. (Chi-square test, $p < .01$.)

24 The massively parallel and von Neumann supercomputers case is taken from Allan Afuah, and James Utterback, "The Emergence of a New Supercomputer Architecture," Technological Forecasting and Social Science, Vol. 40, No. 4, December 1991, pp. 315-328; cases from the cement industry and minicomputer industry, the Owens process and other machinery for glass bottle-making and the direct reduction of iron are contained in Philip Anderson and Michael Tushman. "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change," Administrative Science Quarterly, Vol. 34, No. 4, December 1990, pp. 604-633; transitions from steam to diesel locomotives, vacuum tubes to transistors, fountain to ball point pens, safety razors to electric razors, fossil fuel boilers to nuclear boilers, propellers to jet engines, and natural to synthetic leather are taken from Arnold Cooper and Daniel Schendel. "Strategic Responses to Technological Threats," Business Horizons, Vol. 19, No. 1, February 1976, pp. 61-69; the radial for bias-ply tire case is from Daniel-Guy Denoual, The Diffusion of Innovations: an Institutional Approach, doctoral dissertation, (Boston, MA: Harvard Business School, 1980); the case of photolithographic alignment equipment

is from Rebecca Henderson and Kim B. Clark. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," Administrative Science Quarterly, Vol. 35, No. 1, 1990, pp. 9-30; the case of oriented strand board and plywood is from Henry Montrey and James Utterback, "Current Status and Future of Structural Panels in the Wood Products Industry," Technological Forecasting and Social Change, Vol. 39, No. 4, December 1990, pp. 15-35; transitions from woven to tufted carpet, open to closed body cars, rayon to nylon tire cord, air cooled to hydrogen cooled generators, open hearth to basic oxygen furnaces and other examples from steel making, continuous drawing of copper wire, synthetic gems and small scale production of industrial gases are from James Utterback and Linsu Kim, "Invasion of a Stable Business by Radical Innovation," in Paul Kleindorfer (ed.), The Management of Productivity and Technology in Manufacturing, (New York: Plenum Press, 1986), pp. 113-151; and the case of optical fiber substituting for copper wire is from John McCormack and James Utterback, "Technological Discontinuities: the Emergence of Fiber Optics," in Competitive Strategies in the Telecommunications Industry, (Greenwich, CT: JAI Press, (in press)). All other cases are from the previous chapters and the sources cited there.

[25] Ibid.

[26] The probability that this strong a relationship would be found by chance alone is less than one in one-thousand. (Chi-square test 3,2 vs. 1,0, $p < .001$.)

[27] (This dovetails nicely with McCormack and Utterback's' forthcoming fiber optics data as well), ibid.

[28] This point is disputed by Donald Frey, formerly at Ford who says that Ford persistently sought radial tires from its reluctant suppliers.