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NANO-TECHNOLOGY: A DISRUPTIVE TECHNOLOGY?

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The term "disruptive technology" as coined by Christensen (1997) refers to a new technology having lower cost and performance measured by traditional criteria, but having higher ancillary performance. Christensen finds that disruptive technologies may enter and expand emerging market niches, improving with time and ultimately attacking established products in their traditional markets. This conception, while useful, is also limiting in several important ways.

By emphasizing only "attack from below" Christensen ignores other discontinuous patterns of change which may be of equal or greater importance (Utterback, 1994; Acee, 2001). Further, the true importance of disruptive technology, even in Christensen's conception of it is not that it may displace established products. Rather, it is a powerful means for enlarging and broadening markets and providing new functionality.

In this paper nano-technologies will be considered in their roles as both disruptive and more broadly discontinuous or radical innovation. Various impacts will be assessed with emphasis on enlarged and new markets that may be created.

From Creative Destruction to Disruptive Technology

The term "disruptive technology" as coined by Christensen (1997) refers to a new technology having lower cost and performance measured by traditional criteria, but having higher ancillary performance. Christensen finds that disruptive technologies may enter and expand emerging market niches, improving with time and ultimately attacking established products in their traditional markets. This conception, while useful, is also limiting in several important ways.

Joseph Schumpeter (1939) considered innovation both the creator and destroyer of corporations and entire industries. He was among the ealiest scholars to note the disruptive nature of technological change observing that it could lead to waves of "creative destruction." Cristiano Antonelli, Pascal Petit and Gabriel Tahar (1992) note that, "in his early works Schumpeter 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." 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. In the light of current thinking one might suggest that the former hypothesis is true for areas of emerging product technology and for firms involved in revolutionary product innovation, while the latter hypothesis might well hold for process innovation and product improvement within firms producing standard products and large systems.

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 (1969), by the author (1971) and by Project Sappho (1972), the first extensive study of matched successful and unsuccessful innovations. Cooper and Schendel (1976) were among 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. Cooper and Schendel (1976) noted 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].

Not only do the sales of the established technology decline, but the traditional leaders in the industry typically 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.

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 skills 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 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."

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 studied just such an extreme case in 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 was important in one generation of product figured prominently in the next! Henderson and Clark (1990, p. 9) concluded 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."

While each of the studies reviewed, as well as my own work with Kim (1986), 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. Henderson and Clark usefully 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. Linsu Kim and I (1986) 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.

In a recent and lucid treatment of the failure of established firms Clayton Christensen (1997) describes a framework consisting of three elements. First is a distinction between sustaining and disruptive technologies. Sustaining technologies are those which improve the performance of established products along dimensions of performance that mainstream customers in major markets have historically valued. Disruptive technologies are those which generally under-perform established products in mainstream markets, but they have other features that a few fringe and generally new customers value. Products based on disruptive technologies are typically cheaper, simpler, smaller and frequently more convenient to use. The second element is the potential for established products to progress faster than the market demand as measured by the traditional performance attributes of a product, and eventually to overshoot the market requirements. Thus, the traditional product becomes ever more elaborate, feature laden and complex. Christensen contends that this creates an opportunity for the so called disruptive technology to attack from below and occupy the lower end of the traditional market. Ultimately, as the new technology itself improves it may occupy an ever growing share of the market driving the older product into a shrinking and ultimately profitless corner. Finally, Christensen contends that investment by established firms in disruptive technologies is irrational because: they offer lower margins; they are typically introduced first in emerging or insignificant markets; and the firm's traditional customers don't want and potentially can't use these products.

Clay Christensen's data show 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. Likewise IBM spent heavily to develop the thin film head for its hard disc drives, while DEC did likewise. 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 systems architectures using established components. The leaders in incremental innovation were not able to keep that proprietary, but this 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 architecture? Because the new architecture did not address the needs of their established customers. Smaller drives at first were much slower and more expensive, but they did enable a hard drive on the desk top. 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. (Afuah and Utterback, 1991)

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 and a road to failure depending on circumstances. These are good lessons to follow in promoting evolutionary change in well understood product lines. But when applied to a disruptive technology they may lead a strong firm into a dangerous trap.

Disruptive Technologies: an Expanded View

Christensen's concept is seductive due to the clarity of its examples and its claimed power and generality (Christensen, Johnson and Rigby, 2002). However, by emphasizing only "attack from below" Christensen ignores other discontinuous patterns of change which may be of equal or greater importance (Utterback, 1994; Acee, 2001). Even a cursory tour of discontinuous innovations yields examples of important new products and markets that do not conform to the "disruptive" pattern. These include consumer goods such as the compact disc, tools such as the electronic calculator, components such as the fuel injector, and commodities such as wafer board and oriented strand board construction panels. Each of these examples has either completely replaced its earlier competitor: vinyl records, the slide rule, and the carburetor, or is rapidly in the process of doing so in the case of plywood for construction.

None of the examples cited above, at least initially, was a case in which cost and traditional performance was lower, but performance along added or ancillary dimensions higher. The electronic calculator provides an almost purely opposed case in which cost was much greater but performance was also greatly enhanced. Early electronic calculators had many disadvantages including weight, complexity, need for electrical power and heat dissipation. Nonetheless, they rapidly improved, and traditional manufacturers of slide rules were rapidly forced out of business (Acee, 2001). The fuel injector for gasoline engines was not only more costly for greater performance along traditional dimensions, but also offered immediate ancillary benefits. Digital cameras provide an example of a more expensive technology with lower traditional performance, but higher ancillary performance for editing, storing and transmitting images. Christensen, et al. (2002) believe that this technology is misdirected, and that a simpler version would address more potential new users. Nonetheless, digital photography is growing rapidly while its costs rapidly decline.

Acee (2001) analyzed these and other cases using the dimensions proposed by Utterback (1994) and by Christensen (1997) as shown in the Table below. Some of the cases are more complex. For example, shortages of raw material led to the search for new forms of wood composite panels for construction. At first an inferior product, wafer board made small inroads into the market for plywood. Later, a superior product, oriented strand board, completely displaced wafer board (Montrey and Utterback, (1990) and now enjoys a share of the market for structural panels about equal to that for plywood.

Some cases are difficult to imagine without external constraints, such as a product with higher costs and inferior traditional and ancillary performance. Several exceptions that prove the rule do seem to exist such as the production of gasoline from coal when supplies of petroleum are limited by war or economic sanctions.

Table: A map of possibilities of competitive advantage due to technological change.

Cost	Traditional Performance	Added Performance	Examples
Lower	Lower	Higher	Christensen Hard Disc Drive
Lower	Higher	Higher	Compact disc/ vinyl album
Lower	Lower	Lower	Wafer board/ plywood
Lower	Higher	Lower	Oriented strand board/plywood
Higher	Lower	Higher	Digital/ film camera
Higher	Higher	Higher	Fuel injection/ carburetor
Higher	Lower	Lower	Wartime substitutes
Higher	Higher	Lower	Electronic calcu-lator/slide rule

Disruption of Markets or Expansion of Markets?

Innovations which broaden the market create room for new firms to start. Utterback (1996, Chapter 9) shows that disruptive innovations that expand markets will almost always come from outside the industry. Christensen (1997) notes that ninety percent of the growth of the hard disk drive market from 1976 through 1989 went to innovators addressing emerging markets. He more recently suggests "companies seeking to create disruptive growth should search for ways to compete against non-consumption: people's inability to use available products and services because they are too expensive or too complicated. It's much easier to target potential consumers who aren't buying at all than to steal customers from an entrenched competitor (Christensen, *et* *al.*, 2002)." The true importance of disruptive technology, even in Christensen's conception of it is not that it may displace established products. Rather, it is a powerful means for enlarging and broadening markets and providing new functionality.

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 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. 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. (Utterback, 1994)

Some discontinuities create a wholly new market niche, encouraging the entry of many new entrants. Here, established firms are unlikely to enter successfully and new firms have greater survival odds. The term new firm in Utterback's usage has a specific meaning, including large firms entering markets in which they have no previous stake. Examples include: Corning in optical fibers; Remington in typewriters; and General Motors in diesel-electric locomotives.

In Christensen's theory of disruptive technology the establishment of a new market segment acts to channel the new product to the leading edge of the market or the early adopters. Once the innovation reaches the early to late majority of users it begins to compete with the established product in its traditional market. Here we have presented an alternative scenario in which a higher performing and higher priced innovation is introduced into leading established market segments and later moves toward the mass market. Diffusion of, for example, fuel injection started with the luxury and sports car segments and then migrated into other segments.

The first use of electronic calculators was in the scientific community. Later simpler, less expensive and portable models expanded the total market by creating new segments which later included the mass market. Cooper and Schendel similarly discuss the down-market progression of the ball point pen which was originally more expensive than the fountain pen. Continued development resulted in the "throw away" pen which opened up new market segments. (Acee, 2001, p. 43)

Nano-technology as an Example

This paper set out to consider nano-technologies in their roles as both disruptive and more broadly discontinuous or radical innovation. Various impacts were to be assessed with emphasis on enlarged and new markets that may be created. In retrospect this goal seems premature. Much of what passes for nano-technology seems in fact more to be nano-science. Perhaps due to generous funding of a perceived breakthrough area much that might be done under other headings seems to have been swept under the banner of nano-technologies making the very meaning of the term extremely difficult to define. Finally, little effort seems so far to have gone into manufacturing techniques and strategies for reducing promising scientific findings to practice. Those approaches that have been used to make significant amounts of small particles are often the well known paths of colloidal chemistry. Much of what is currently being produced seems more for laboratory study than for practical use and lacks many related and supporting technologies required for reduction to practice. (***Science***, 21 December, 2001, ***Scientific American*** special issue on "Nanotech," September 2001).

Surely our ability to sense and manipulate atoms and molecule will ultimately lead to wholly new markets and newly enabled markets. This seems especially the case in pharmaceuticals and medicine, though the ultimate impacts can only be guessed. Among the many possibilities being discussed many seem to be sustaining technologies by the definitions above. These include in the authors' opinion highly engineered catalysts, tougher ceramics and diamond tools based on compounds of extremely small particles or crystals, means to record much more data on disk drives, and better ultra-violet protection from the inclusion of nano-particles in cosmetics. Perhaps not incidentally, these developments are primarily identified with larger firms: Exxon, (Nanophase Technologies), IBM and L'Oreal.

Other possibilities seem to be disruptive technologies of various sorts by the definitions above. These include in the authors' opinion polymeric solar cells, polymeric circuits, polymeric light emitting diodes, and electro-mechanical technologies for exquisitely identifying scents and volatile compounds. Perhaps not incidentally, these developments are primarily identified with new firms: Cambridge Display Technologies, Plastic Logic, Konarka, Uniax, E-Ink, Rolltronics (and IBM). (Seminar at Cambridge University, April 26, 2002)

Clearly it is too early to determine the directions any of these possibilities may take. New technologies are seemingly always viewed as substitutes at first. We will only know their true meaning through a great deal of experimentation in use. Disruptive technologies open whole new frontiers and markets that we discover only through making diverse connections.

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