Chapter 1

Disruptive Technologies: An Expanded View*

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The term “disruptive technology” as coined by Christensen (1997, *The Innovator's Dilemma; How New Technologies Cause Great Firms to Fail*. Harvard Business School Press) 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 emphasising only “attack from below” Christensen ignores other discontinuous patterns of change, which may be of equal or greater importance (Utterback, 1994, *Mastering the Dynamics of Innovation*. Harvard Business School Press; Acee, 2001, SM Thesis, Massachusetts Institute of Technology). 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 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

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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 present an alternative scenario in which a higher performing and higher priced innovation is introduced into the most demanding established market segments and later moves towards the mass market.

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From Creative Destruction to Disruptive Technology

Schumpeter (1939) considered innovation both the creator and destroyer of corporations and entire industries. He was among the earliest scholars to note the disruptive nature of technological change observing that it could lead to waves of “creative destruction”. Antonelli *et al.* (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, utilisation of new raw materials, or even the reorganisation of a sector of the economy”. They continue, “this initial approach stressed the discontinuities of the innovation process”. In later years Schumpeter (1942) 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 (1969) in their influential study, by Utterback (1971) and by Rothwell *et al.* (1974), 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 the case when clearly the traditional firms are financially strong and possess sophisticated market knowledge and distribution channels?

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. However, the balance of evidence does not seem to support this view.

For example, Cooper and Smith (1992) found that all of 27 defending firms in seven industries studied entered the fray to develop products based on disruptive technologies, 21 of them entering early in the game. Few of the established companies succeeded in the end. Cooper and Smith, while considering the capabilities, argue that the compelling reason for failure was the way in which firms' historic experiences affect their perceptions about how to compete in the emerging field. Established competitors seldom expect that a disruptive technology will penetrate the core markets of the traditional business. This is amplified in Cooper and Smith's findings when firms keep groups together reinforcing this misperception, and when they choose incorrect strategies. They conclude that folding the new product into historic strategies and channels also hampers success, especially when the new technology in their words makes possible different

concepts or ways of competing. Utterback's (1994, Chapter 9) analysis of discontinuous changes in 41 different technologies found that competence destruction or enhancement, while important, was the least powerful variable in indicating whether incumbents or new entrants were the innovators. The degree to which the market was expanded by the innovation seemed to be the strongest factor favouring new entrants.

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 organisation are loaded with implications for the decision makers; not only are old product lines threatened, but also old skills and positions of influence".

Allocation of resources for renewal when core products are threatened may be one explanation of the "sailing ship effect" first identified by Gilfillan (1935) in his seminal study on inventing the ship and later made popular by Foster (1986). They suggest that existing players are often aware of approaching discontinuities, but still pursue their current trajectories with success in the short term. Utterback (1994) hypothesises that to some extent the renewal of the old may in part be a function of its adopting and incorporating the new, but as a defensive measure. A current example is the degree to which film camera makers have adopted electronics to provide enhanced features such as automatic exposure, focusing, film advance and so on. In part, the resurgence of the old may be a function of picking up opportunities that have lain fallow when just incremental improvement seemed to suffice. Another possible explanation is that many market niches for an older technology may be protected for a long period of time. These would necessarily be the niches in which it has the greatest

advantages over the disruptive technology, as in say film for professional photography. Since improvement would have greater value in these niches, one might actually observe more rapid advance in the traditional technology for that reason. This seems to have been the case in the response of carburetor technology to the threat posed by the spread of fuel injectors (see Kash and Auger in this issue).

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 characterised 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 important firm 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 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 organisations, this destruction is difficult for firms to recognise and hard to correct”.

Dosi (1982) introduced the concepts of technology paradigm and technology trajectories in his attempt to account for continuous and discontinuous technological change. He defined technology paradigm as “an outlook, a set of procedures, a definition of the relevant problems and of the specific knowledge related to their solution”. Technology trajectory is defined as “the direction of advance within a technology paradigm”. Dosi promoted a holistic view of technology change, which is characterised by a complex structure of feedbacks between the economic environment (markets, governments, etc.) and the direction of technological change. He notes that once established, technology paradigms have a significant

exclusion effect, that is, the efforts and imagination of engineers and their organisations are focused in a rather precise direction and blind to other technological possibilities. As economic and social conditions change they interact with the process of selecting new technologies, with their development, and with their eventual obsolescence and substitution. The change from one technological paradigm that has shaped a firm, as described above, to a new paradigm formed by economic and social change presents a significant challenge for incumbent firms.

While each of the studies reviewed, as well as Utterback's 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. They 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 organisation that can learn quickly and effectively about components may not be able at all to fathom systems relationships. Utterback and Kim (1986) concluded that discontinuities that break market and manufacturing process linkages will be more threatening to the firm than those that 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 that expand the market are seemingly less threatening to established firms than are those that simply create substitute products. This perception may lead established firms to wrongly minimise their significance.

In a lucid treatment of the failure of established firms, Christensen (1997) describes a framework consisting of three elements. First is a distinction between sustaining and disruptive technologies. Sustaining technologies are technologies that improve the performance of established

products along dimensions of performance that mainstream customers in major markets have historically valued. Disruptive technologies are those that 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 is forced to retreat to the higher end of the market becoming 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 do not want and potentially cannot use these products.

Clayton 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 Clark's 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 them 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?

The hypothesis is that new architecture did not address the needs of established customers! Smaller drives at first were much slower and more expensive per byte of data stored, but they did enable a hard drive on the desktop for an affordable total cost. Christensen finds 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, 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 powerful concepts for success or a road to failure depending on circumstances. These are lessons to follow in promoting evolutionary change in well-understood product lines. But when applied to products threatened by a disruptive technology they may lead even a strong firm into a dangerous trap.

Our analysis here applies only to tangible products already in the market, which are being challenged by a new concept aimed generally towards the same end or function. Kash and Auger elsewhere in this issue define transformative innovations, which establish whole new sets of values and functions, coming out of left field so to speak. Similarly, Utterback (1994) describes radical innovations that essentially set aside all past practice in a field such as did the transistor. Though fascinating and important patterns of change, these are not the subject of our analysis. Nor are they encompassed in Christensen's (1997) definition of disruptive technology. Christensen does briefly discuss disruptive innovations in services. We think this generalisation stretches his model too far, or rather that services present mostly different dynamics than do tangible products. We are reluctant to extend our present analysis to innovation in intangibles.

Disruptive Technologies: An Expanded View

Christensen's concept is seductive due to the clarity of its examples and its claimed power and generality (Christensen *et al.*, 1998, 2002; Christensen and Raynor, 2003). However, by emphasising 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 were 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) analysed these and other cases using the dimensions proposed by Utterback (1994) and by Christensen (1997) as shown in the Table 1. If we consider the dimensions of cost, traditional performance and ancillary performance, we can construct the eight rows of the matrix presented. 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 product superior to wafer board, oriented strand board, completely displaced wafer board (Montrey and Utterback, 1990). It now enjoys a share of the market for structural panels about equal to that for plywood.

Table 1. A map of possibilities of competitive advantage due to technological change.

Cost	Traditional performance	Ancillary performance	Examples
Lower	Lower	Higher	Christensen case Hard disc drives
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 calculator/slide rule

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.

The matrix illuminates a few areas of interest, most notably the category illustrated by fuel injectors in which all parameters are greater than the current technology. The category of lower cost and greater performance, both traditional and ancillary, is illustrated by the recent disruption of the CD over vinyl LP and tape recording media. These illustrations clearly show the possibility of disruptive attack from above. In the following sections, we will examine a case in each category in detail in order to illustrate the range of possible variations of disruptive technologies that may actually be observed.

Compact Disrupt Vinyl Record Albums and Tapes

In 1969, Dutch physicist Klaas Compaan at Philips Laboratories used a glass disc to store black and white holographic images using frequency modulation. Four years later, in 1973, Philips engineers began to contemplate an audio application for their “video” disc system. A prototype disc with a 44 kHz sampling rate was run through a 14-bit digital-to-analog converter and exhibited a signal-to-noise ratio of 80 dB in monaural.

Mitsubishi, Sony and Hitachi all demonstrated digital audio discs at the Tokyo Audio Fair in 1977. One year later, Philips joined with its recording subsidiary Polygram Records to develop a worldwide digital audio standard and in March 1979 demonstrated a prototype compact disc player in Europe. Sony joined the Philips/Polygram coalition after Matsushita declined and in June of 1980 the coalition formally proposed their CD standard. A year later Sharp successfully mass produced the semiconductor laser. This step was crucial to delivering a consumer product. In the fall of 1982, Sony and Philips introduced their respective players to consumers in Europe. The system was introduced in the United States in the spring of 1983 and 30,000 players and 800,000 compact discs were sold that year.

Up to this point audio storage was analog in nature and primarily comprised of the use of long playing vinyl records. Vinyl records store information as a groove where variations in its direction and depth represent the original audio signal. A stylus runs through the groove and its mechanical movements converted into an electrical signal that is amplified. The very nature of the analog signal leads to its own shortcomings. In the analog domain any waveform is allowable; therefore, the playback mechanism has no means to differentiate noise and distortion from the original signal. In an analog system every copy made introduces more noise than its parent. This fact is due to both the playback and recording mechanism that must physically contact the media, further damaging it after every pass.

An advantage of the digital audio signal is that noise and distortion can be separated from the audio signal. A digital audio signal's quality is not a function of the reading mechanism or the medium. In short, the traditional performance attribute of sound quality is better for a compact disc compared to a vinyl record. The ancillary performance of increased play durability reduced handling damage susceptibility and compact size yields higher compact disc value.

The initial high price of a CD player relative to a record player and the existing vinyl libraries owned by individuals limited CD system sales during introduction. In 1984, Sony introduced the Discman, and the subsequent introduction of CD radio-cassette players and car CD players enhanced the value of the CD system by allowing the CD to go where

records could not. Sony, also a major supplier of “key components” (such as optical pick-up, laser diode and LSI), began to lower prices to the hardware manufacturers based on anticipated savings allowing a reduction in hardware prices. This combination of hardware prices approaching that of traditional record players and promotion of the ancillary benefit of mobility spurred the market for CD systems.

Currently, the new MP3 compression format is challenging the compact disc standard in some market segments. The MP3 format carries much less information and fidelity to the original music than does a compact disc. It is much easier to store and is cheaper and easier to transmit digitally. This has opened up new channels for music sale, storage and portability. For example, one company, Garage Bands, features the music of new and little known groups. Other musicians are selling their music directly over the internet. This seems to be a disruptive innovation as judged strictly using Christensen’s restrictive definition.

Wafer Board Disrupts Plywood

Montrey and Utterback (1990) examined innovation in the structural wood panels market leading to the introduction of wafer board and later oriented strand board as substitutes for plywood and provide a historical overview of these developments. After World War II, plywood, which had been introduced over 40 years earlier, began to be used in light frame construction in increasing volumes in North America. The structural flexibility inherent in the plywood panel and its lower overall installed cost resulted in the displacement of lumber as the dominant sheathing material for floor, wall and roof construction. Rapidly increasing timber prices through the 1970s and early 1980s resulting from shortages of adequate timber to produce the plywood veneer coupled with increasing labour, energy and adhesive costs resulted in severe plywood price inflation during this period. Known and rapidly developing processes for the production of particleboard and fibreboard had demonstrated the ability to produce flat structural panels that could potentially be a substitute to plywood. These process technologies, along with declining plywood quality, abundant timber sources suitable for particleboard fabrication and new product

performance standards provided an impetus to new structural panel development.

Perhaps wafer board should not be considered exactly a disruptive technology. It is an entirely inferior good compared to plywood recommended only by its low price. It was given entrée into the market by shortages of high-quality veneer used to make plywood. During the energy crisis of the early 1970s a similar situation arose from shortages of fibre-glass insulation, which provided an entrée for cellulose substitutes. Once in the market, however, these competitors proved difficult to dislodge.

Oriented Strand Board Disrupts Wafer Board and Plywood

Oriented strand board is an un-veneered structural panel comprised of three layers of aligned strands that are similar to wafers but are longer. The strands are basically wafers that have been split across the wood grain so that they are much longer in the natural grain direction than across the grain. The strand layers then alternate direction to give oriented strand board a construction that mimics plywood.

Oriented strand board offers a lower cost when compared to plywood due primarily to the use of lower cost timber. As a result, oriented strand board panels can be load-bearing members in end-use, the traditional performance measure is strength and stiffness, which for oriented strand board is slightly more than that of plywood. The ancillary performance of the structural panel is weight, dimensional stability and durability. Oriented strand board is heavier than plywood, is more prone to thickness swelling and its durability is slightly less than plywood. In general, its ancillary performance is lower than that of plywood. Oriented strand board was commercially introduced in 1981. By 1996, wafer board had been replaced in large part by oriented strand board, and strand board production was increasing dramatically. The structural panel market was evenly split between plywood and strand board in 1998, while the price of plywood was roughly 20 percent higher than strand board.

The case of oriented strand board and plywood differs from previous cases in that a structural panel is a non-assembled product and that the technological innovation involves the process to a greater extent than the

product. The development of new process technologies allowed structural panel manufacturers to produce a low-cost plywood substitute. However, the plywood producers retaliated by making process improvements that lowered their production costs thereby remaining competitive with oriented strand board. The major issue for plywood is veneer timber price and availability, which continues to push plywood into higher-value products leaving the market for sheathing, sub-flooring and other panel applications to oriented strand board.

Digital Cameras Disrupt Silver Halide Film

The single functional model for conventional photography has been replaced by at least four paths: capture/view/verify; capture, share; capture, print, share; or capture, share, print. The process unit for digital photography can be as small as one picture or as large as the capacity of one's memory card. There is no economic penalty to taking and later discarding images. The captured image can be viewed on the camera's display immediately and can optionally be printed on personal portable or desktop printers as soon and as often as desired, or sent to one of the traditional print fulfillment venues electronically. Traditional print fulfillment uses the same standard output formats as traditional film, but direct thermal, inkjet and desktop printing are unconstrained. New photo-kiosks and digital mini-labs are emerging as alternatives to the one-hour film labs in malls and retail outlets. The user can bypass printing and share or store the image electronically via any number of digital information networks, via a personal computer or in some cases directly device to device.

The easy transmission and sharing of images creates almost endless possibilities for new enterprises — pictures on mugs, calendars, cakes, business cards, greeting cards, electronic picture frames in consumer markets; instantaneous and ubiquitous advertising in commercial markets; and distributed yet connected security, documentation and information sharing for business and government.

The advantages of digital imaging explain its rapid adoption in commercial applications, but the complexity of the new digital photography paths may help to explain its failure to displace conventional photography in the broader consumer market.

While one can find some parallels with the story of the digital camera, it is typically brought up as a counter-example to Christensen's theory. This is because of the higher cost and complexity of the digital camera relative to conventional photography, which given Christensen's arguments might exclude it from being a disruptive innovation. Whether or not it is seen as disruptive under Christensen's model, digital photography is undoubtedly innovative and has disrupted the way money is made in the photographic industry.

Fuel Injectors Disrupt Carburetors

The early development of the automobile incorporating the internal combustion engine based on the Otto cycle (four cycle, spark ignition) and a carburetor to control fuel delivery became what Utterback and Abernathy (1975) termed a "dominant design". The development of compression ignition by Diesel led to fuel injection delivery systems for compression ignition engines. The advent of World War II led to major developments in the use of fuel injection in aircraft power systems. In 1957, we believe the Bendix Corporation produced the first commercial electronic gasoline fuel injection system for the AMC Rambler. In 1957, Chevrolet and Pontiac offered an optional "Ramjet" mechanical port fuel injection system. On the Corvette it boosted output to the magic one horsepower per cubic inch, but it was not exactly trouble-free and was often replaced in the field with a big carburetor. In 1958, a limited edition Dodge 361 engine had Bendix electronic fuel injection, but less expensive mechanical injection was offered the next year.

Robert Bosch GmbH licensed some fuel injection technology from Bendix and in 1967 introduced electronic gasoline injection into the automotive market with its D-Jetronic system that was installed in the Volkswagen 1600 Model 3 vehicles that were destined for California (which at this time had stringent emission standards). By 1976, fuel injection was standard equipment on Saab and Volvo vehicles and was being offered as an option on some General Motors vehicles. The premium price for fuel injection over carburetion was 600 to 700 dollars. General Motors offered fuel injection as standard equipment on the 1976 Cadillac Seville

that had a list price of \$12,500. General Motors' first production vehicles offered with its version of fuel injection, Tuned Port Injection, were sports cars including the Corvette, Pontiac Firebird and Trans AM, and the Chevrolet Camaro. General Motors claimed that Tuned Port Injection increased horsepower, torque and fuel economy by up to 30 percent over carburetor systems. Independent laboratories verified these claims with the typical improvement in each area being approximately 35 percent better than carburetor systems.

The late 1970s and early 1980s saw mounting environmental pressure by United States government legislators and increasing fuel efficiency concerns. The auto industry in response to these pressures adopted fuel injection as the primary fuel delivery system over carburetion. Bosch, which was traditionally a manufacturer of ignition and electrical systems (not carburetors), geared up fuel injection system production in its Charleston, South Carolina plant. Walbro Corporation, a manufacturer of carburetors for lawn mowers, weed whackers and chain saws (not auto parts), entered the automotive fuel storage and delivery business. Pierburg AG, a European carburetor manufacturer, is now a throttle body manufacturer and competes with Walbro in products such as fuel pumps and fuel modules. The General Motors (Rochester Products Division) and Ford parts operations were also able to shift technologies from carburetion to fuel injection. However, some companies, like Holley, could not negotiate the change in technology and switched from carburetors to transmission control solenoids, emissions valves and throttle bodies, resulting in a major contraction in the size of the firm.

In 1980, about 7 percent of the cars in the US market were equipped with fuel injection, which increased to 96 percent in 1990 and to approximately 100 percent by 1993. The changing operating environment of the automobile drove the adoption of fuel injection, that is, greater concerns for the environment and fuel conservation. Fuel injection provided the consumer with increased automobile traditional performance attributes of increased engine power, fuel mileage and reliability along with the ancillary performance attribute of reduced emissions at a price premium over traditional carburetor systems. Fuel injection was a disruptive technology in that it dramatically differed from the incumbent carburetor-based technology. Fuel injection represented an architectural change in the fuel

delivery system as well as a change to the system components when compared to carburetion.

Electronic Calculators Disrupt Slide Rules

The introduction of the scientific calculator, while priced significantly higher than the slide rule, displaced slide rule technology as a result of performance advantages that included greater accuracy and speed of calculation, which appear to be the slide rule's traditional performance considerations. The ancillary performance benefits of the hand-held calculator over the slide rule include ease of use, ease of learning, visibility of output and greater functionality. The hand-held calculator attacked the slide rule in its mainstream market, science and engineering professionals and students. As a result of falling prices and ancillary performance attributes (most notably ease of use and ease of learning), the calculator market rapidly expanded into the mass consumer market.

The displacement of the slide rule by the electronic calculator resulted in the elimination of the slide rule industry as a result of the comparatively radical innovation of electronic technology over the traditional mechanical technology employed by the slide rule product. In this example, the disruptive electronic technology resulted in overall greater product performance although at a higher price than the incumbent product technology. As a result, we may conclude that the performance demanded by the mainstream market was unmet by the incumbent product technology and that the introduction of a new product technology, which fulfilled that unmet need, was valued by the market as evidenced by the support of the higher product price.

Disruption of Markets or Expansion of Markets?

Innovations that broaden the market create room for new firms to start. Utterback (1994, Chapter 9) shows that disruptive innovations that expand markets will almost always come from outside the industry. Christensen (1997) notes that 90 percent of the growth of the hard disk drive market from 1976 through 1989 went to innovators addressing emerging markets.

He more recently suggests that “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 in Utterback’s (1994) and in Christensen’s (1997) 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 20 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. In such a case 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 fibres; 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 early adopters in that market. Once the innovation reaches the early to late majority of users it begins to compete with the established product in its traditional market.

Cooper and Schendel (1976), in contrast, present the down-market progression of a number of disruptive products including 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. Here, the authors have presented an added example in which a higher performing and higher priced innovation is introduced into leading established market segments and later moves towards 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.

In summary, we have stated the complete set of nodal patterns defined by three variables (given in Table 1) and shown that illustrations of disruptive technologies can be found that match each of the nodes. This is true even for cases one might expect *a priori* to be null, such as those with higher cost but inferior performance on all dimensions, though the only examples we discovered arose from instances of constrained supply of raw materials. Perhaps cases of attack from below have greater potential for explosive growth than do those of attack from above, but in either pattern we can observe instances of dramatic market expansion. And dramatic market expansion seems to be a hallmark of some of the mixed illustrations as well. In some respects it seems that in past work on discontinuous or disruptive innovation our perceptions have been a bit like those of the eight blind men encountering the elephant. The beast as a whole may turn out to be more complex and interesting than it first appeared.

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