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Reconciling Discontinuities and Disruptions: The Construction of an Integrated Typology

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RECONCILING DISCONTINUITIES AND DISRUPTIONS: THE CONSTRUCTION OF AN INTEGRATED TYPOLOGY

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ABSTRACT

RECONCILING DISCONTINUITIES AND DISRUPTIONS: THE CONSTRUCTION OF AN INTEGRATED TYPOLOGY

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Radical innovations are often characterized by a rapid shift from one dominant design to another. The theories of discontinuous and disruptive innovation present two important and independent explanations for why these shifts occur. This research tests the usefulness of combining these two theories into a single integrated typology. First, a typology is constructed that classifies shifts in dominant designs according to the theories of discontinuous and disruptive innovation. Next, the usefulness of this typology is tested with a taxonomy derived from 100 randomly selected shifts in dominant designs from across a broad range of industries. This research reconciles the theories of discontinuous and disruptive innovation and proposes an integrated typology to assist managers in determining the circumstances under which each theory is best applied. Additionally, the resulting taxonomy suggests anomalies - shifts in dominant design that are not well classified by either theory - that illuminate promising avenues for future research.

This dissertation is dedicated with all my love to my wife, Pamela, and my children, Michael and Margaret. Innovation may bring change, but love is constant.

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INTRODUCTION

Research Problem

The theories of discontinuous and disruptive innovation serve as foundations for a large body of research into how radical innovations occur. Unfortunately for engineering and technology managers, these important theories are not well integrated. Are these theories completely independent? Are there circumstances where both apply? Where neither applies? This dissertation explores what these theories are, how they evolved, and proposes an answer to these questions.

The theory of discontinuous innovation models the emergence of a new dominant design as an evolutionary cycle (Anderson & Tushman, 2001; Dosi, 1982; Romanelli & Tushman, 1994) where periods of incremental innovation are interrupted by the introduction of technological advances or discontinuities. Industry turmoil ensues as the discontinuity is incorporated into various candidate designs. Eventually, a new dominant design emerges and signals return to an era of incremental innovation.

The theory of disruptive innovation models the emergence of a shift in dominant design as part of a disruptive cycle where the interplay of technological and market forces create disruptive opportunities for new designs (Christensen, 1997; Christensen & Raynor, 2003a). Incumbent firms pursue improvements to their products in order to satisfy their most demanding customers. Over time, the technological performance of the product exceeds the demands of many customers. At this point, new entrants to the

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market that have created technologically inferior but market satisfying designs are able to invade the primary market and shift the market's dominant design.

The existing literature does not consistently integrate these two theories. Sainio (2004) emphasizes the similarities in these theories. She notes that both discontinuous and disruptive innovations are capable of transforming existing markets or creating new markets as new dominant designs emerge. According to Sainio (2004), firm competencies distinguish discontinuous innovations from disruptive innovations. Discontinuous innovations are either competence-enhancing or competence-destroying (Tushman & Anderson, 1986), while disruptive innovations are always competence-destroying for established firms within the market.

Henderson (2006) focuses more specifically on the types of competencies that might distinguish discontinuous from disruptive innovation. She notes that discontinuous innovations impact the technological competencies of the industry while disruptive innovations impact market competencies. However, while firm competencies may be closely linked to which firms survive the innovation (Anderson & Tushman, 1990; Henderson, 2006; Tushman et al., 1986), other economic or technical factors may play a larger role in the emergence of the dominant design in the marketplace (Adner, 2002; Henderson, 2006).

The theories present themselves as distinct, independent phenomenon. Christensen (2006) argues that disruptive innovation is often misinterpreted by researchers because the word "disruptive" has a more general connotation. From the perspective of disruptive theory, discontinuous innovation is classified as sustaining. The theory of discontinuous innovation (Tushman et al., 1986) was developed before

Christensen published his theory and is silent on the subject. More recent publications by the authors of discontinuous innovation describe disruptive innovation as specific phenomenon in a more general description of innovation (Gatignon, Tushman, Smith, & Anderson, 2002).

Research into each of these theories continues largely independently. This is a problem because different researchers continue to classify radical innovations differently (Dahlin & Behrens, 2005; Garcia & Calantone, 2002). This has the potential of confounding the results of innovation research and confusing practitioners. A comprehensive classification scheme is needed that integrates the theories of radical innovation for engineering and technology managers. As Garcia et al. (2002: 111) point out,

> Because new product researchers have not found consistency in labeling and identifying innovations, we cannot expect practitioners to have learned from our research endeavors. Managers looking for an understanding of how to address the idiosyncratic problems associated with radical innovations will have difficulties finding the holy grail from our research efforts.

Purpose

The purposes of this study are to (a) construct a typology that engineering and technology managers can use to integrate the theories of discontinuous and disruptive innovation by classifying shifts in dominant designs and to (b) test the usefulness of this typology with a quantitatively constructed taxonomy. The interdependent variables of the typology are derived from each theory of innovation. The objects of the taxonomy that is used to test the integrated typology are shifts in dominant designs that are predicted by both theories.

Significance of Research Problem. Innovations are an important economic engine and a source of competitive advantage. From the time of Schumpeter's description of innovation as "creative destruction," researchers have searched for theoretical structures to guide the development of innovations (Scherer, 1992). The market implications of discontinuous innovation are significant while our ability to develop business strategies to take advantage of discontinuity remain limited (Bessant, Birkinshaw, & Delbridge, 2004; Bessant, Lamming, Noke, & Phillips, 2005). The opposite is true in the case of the theory of disruptive innovation. Several case studies indicate that market strategies based upon the theory of disruptive innovation have been effective (Christensen, 2006) while critics show concern for potential weaknesses in the disruptive body of knowledge (i.e. generalizability, selection bias, etc.) (Danneels, 2004).

McKelvey (1975: 573) explains how generalizability improves with an adequate classification scheme:

> If a useable classification existed, there would be no need for contingency theory. Biologists do not need contingency theories because their taxonomy and classification scheme makes it clear that one does not apply findings about reptiles to mammals unless one is dealing broadly with the subphyla level of invertebrates. Organization and management theorists need contingency theories because there is no taxonomy to make clear that one does not, for example, and only for example, apply findings from small British candy manufacturers to large French universities.

The theories of discontinuous and disruptive innovation are de facto classification schemes. The presence of independent classification schemes that have not been reconciled hampers the practical application of these theories in real-life, multi-dimensional organizations (Carper & Snizek, 1980). A validated typology that integrates the two theories will aid engineering managers who want to apply these theories in their practice and contribute to a more general understanding of innovation.

Contributions to Knowledge and Practice. Hass et al. (1966) note that a well constructed organizational taxonomy would "(1) be strategically helpful for refining hypotheses; (2) aid in the investigation of the validity and utility of existing typologies based on logical and intuitive considerations; (3) serve as a basis for predicting organizational decisions or change; and (4) permit researchers to readily specify the universe from which their samples of organizations could be drawn" (Carper et al., 1980: 73). This research proposes that an empirically validated system of classification reconciling the theories of discontinuous and disruptive innovation will:

- Provide confirmatory analysis by validating the results of the typology deduced from existing theory, thus extending the generalizability of both theories.

- Assist Engineering and Technology Managers in understanding how and when to apply these theories of radical innovation to the complex situations that they encounter.

- Enable researchers to better understand the circumstances under which each theory holds sway or if there are circumstances where both theories (or neither) should be considered.

- Examine the resulting data structure to explore potential relationships between the two theories and to guide further research.

Research Questions

This dissertation explores the following descriptive questions with regard to the theories of disruptive innovation and technological discontinuities:

1. What is the current state of research into these theories? What is known and what remains open to research?
2. What typology can be deduced from these two theories?
3. To what extent does the resulting taxonomy confirm the theories of discontinuous and disruptive innovation?
    a. Are the theories of discontinuous and disruptive innovation substantiated?
    b. Are there cases of shifts in dominant design where both theories seem to operate?
    c. Are there cases where neither theory seems to operate?

Additionally, this dissertation explores several inferential questions:

4. What does the data structure infer regarding our understanding of discontinuous and disruptive innovation?
5. What relationships appear to exist between these two theories? How might these theories be altered to better fit the empirical data? What new theories are required?

Definitions

Taxonomy. Taxonomy – the science of classification – partitions and labels "many different items into groups or clusters that share common traits" (de Jong & Marsili, 2006: 214). Classification systems or taxonomies are useful for two reasons (Copi, 1972). First, for practical reasons, taxonomies help us retrieve information. Second, they help highlight similarities and differences in the topics being researched. The primary criticism of taxonomy as a classification system is that it is inherently descriptive, but while taxonomies may not constitute theory (Doty & Glick, 1994), they may well constitute a hypothesis (Copi, 1972).

Typology. The terms typology and taxonomy are sometimes used interchangeably and sometimes used with specific meaning (Rich, 1992). This research chooses the latter approach. A typology is an *a priori* classification scheme constructed from theory (Miner, 2002; Rich, 1992). It depends heavily upon rational argument as opposed to empirical analysis of data. A system of classification that is theoretically derived and populated with empirical data is considered in this research to be a typology. A taxonomy is an empirically derived categorization often using multivariate analysis of existing data (Miner, 2002). In short, typologies *explain* and taxonomies *describe*.

Radical Innovation. There is no consensus on the definition of radical innovation (Dahlin et al., 2005; Green, Gavin, & Aimansmith, 1995; McDermott & O'Connor, 2002). Some researchers define an innovation as radical if it incorporates a new technology and meets new market needs (Chandy & Tellis, 1998; Sorescu, Chandy, & Prabhu, 2003); if it is a high risk and costly innovation with little supporting technological or business experience (Green et al., 1995; McDermott et al., 2002); if it is new-to-the-world and has great impact on markets and producers (Markides, 2006); or if the product, the process needed to produce the product, and the service that product provides is new to the marketplace (Mensch, 1985).

Radical innovation is most often represented in the literature as the extreme end of a spectrum of change (Cabello-Medina, Carmona-Lavado, & Valle-Cabrera, 2006). While there is great value in achieving a stable, agreed upon definition of radical innovation (Dahlin et al., 2005), that task lies beyond the scope of this research. When this research refers to *radicalness*, it is intended in the most commonly applied sense - that the radicalness of an innovation is related to the degree of change or newness/novelty of the innovation (Cabello-Medina et al., 2006; Gatignon et al., 2002). Radical innovations are a general category of which discontinuous innovations and disruptive innovations are subcategories.

Dominant Design. Dominant designs are a rare example of a concept upon which there is relative agreement within the literature of innovation. Utterback & Abernathy (1975) describe a dominant design as the event in the life cycle of a market where the multiple designs generated by a new technology are consolidated into a single architecture. Henderson & Clark (1990: 14) describe the dominant design as incorporating " a basic range of choices about the design that are not revisited in every subsequent design." Sahal (1981) describe dominant designs as "technological guideposts" that incremental innovations improve over time. They tend to emerge as a synthesis of "proven concepts from the past" (Sahal, 1981: 309) and the more adaptable the design is to the task environment, the greater the potential advance of subsequent innovations. Dosi (1982) compares the emergence of technological changes to the theory of scientific paradigms (Kuhn, 1962). He argues that dominant designs represent a technological paradigm that shapes the direction of the development of the technology (the technological trajectory) while at the same time establishing boundaries.

It is not clear whether every dominant design is the result of a preceding radical innovation. Abernathy (1978: 57) argues that "... a design approach becomes dominant ...when the weight of many innovations tilts the economic balance in favor of one design approach." Dosi (1982) argues that incremental innovation occurs along the technological trajectory defined by the existing technological paradigm. Radical innovation triggers a technological paradigm shift that results in a new dominant design. Shifts in dominant design are predicted by the theories of discontinuous and disruptive innovation. Many believe that dominant designs can only be identified once they have occurred (Gallagher, 2007).

Discontinuous Innovation. A discontinuous innovation occurs when the trajectory of existing technologies are interrupted by a new technological trajectory (Anderson et al., 1990). This view has been incorporated into the theories of organizational ecology and has supported a punctuated equilibrium theory of radical innovation (Tushman & O Reilly, 1996). From this evolutionary perspective, discontinuous innovation is caused by the introduction of a major new product or service that results in the major changes to the industry. The literature of discontinuous innovation will be examined in detail in the next section.

Disruptive Innovation. The literature of disruptive innovation combines perspectives from the theories of resource dependence (Pfeffer & Salancik, 1978) and resource allocation (Burgelman, 1983) to explain how new products in less capable

(Christensen & Bower, 1996) or adjacent markets (Christensen et al., 2003a) can disrupt existing markets. Disruptive innovations are new products or services that enter the market place with new value propositions. The new value might be reduced cost or new attributes. In either case, the new values invade existing markets and result in rapid shifts to a new dominant design. The effectiveness of a disruptive innovation is heavily linked to the business model that deploys the new product or service (Christensen, 2006). Disruptive innovation will also be examined more closely in the next section.

Theories of Contextual Technology

Gopalakrishnan and Damanpour (1997) describe many perspectives that may be adopted in conducting research into the theories of innovation (See Table 1). This research adopts the perspective of contextual technologists which is consistent with theories of discontinuous and disruptive innovation. Contextual technologists focus on the generation of innovations and how they are commercialized and marketed. They focus on the innovation as a primary attribute within an industry context. They consider primarily technical innovations of both the product and process type. The interactions between innovations and their environments are the primary emphasis of research. As Anderson (1988: 190-191) notes,

> Since the mid-1960s, there has been an underlying agreement among organizational scholars that is usually termed the "open-systems" view. It suggests that organizations cannot be understood independently of their environments. Outcomes arise from the interplay between the organization and its environment, and form the fit between them. Clearly, this fit cannot be static and unchanging. Environments change. So must organizations, populations of organizations, and communities of

TABLE 1
Perspectives in Innovation Research
(Adapted from Gopalakrishnan and Damanpour, 1997)

Perspectives	Stage of Process	Level of Analysis	Type of Innovation
Economists	Generation Idea generation Project definition	Industry	Product/process Technical Radical
Contextual Technologists	Generation Commercialization Marketing Diffusion	Innovation/Industry	Product/process Technical Radical/incremental
Organizational Technologists	Generation Idea generation Problem solving adoption Adoption Initiation	Organizational Sub-system	Product/process Technical Radical/incremental
Variance Sociologists	Adoption Initiation Implementation	Organization	Product/process Technical/admin Radical/incremental
Process Sociologists	Adoption Initiation Implementation	Innovation/Organization	Product/process Technical/admin Radical/incremental

> organizations…The question "how do technologies evolve?" is a subset of the questions "how do environments evolve?".

Gopalakrishnan and Damanpour (1997) classified the theory of discontinuous innovation as belonging to the perspective of the contextual technologists. The theory of disruptive innovation emerged after this research was published, but it also fits best in the contextual technologist's category. The next section of this dissertation expands on this topic by placing the theories of discontinuous and disruptive innovation within the broader perspective of the theories of contextual technology.

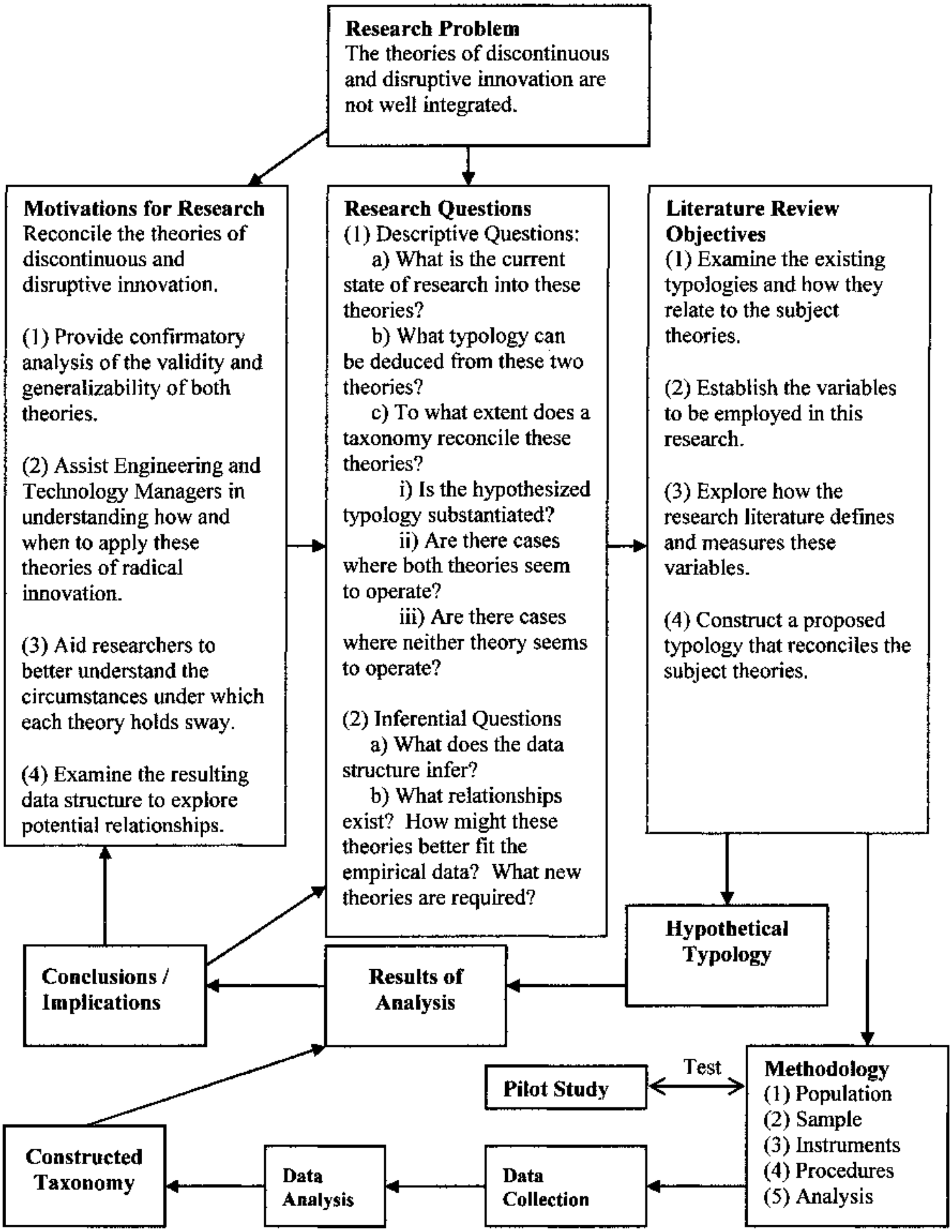
Organization of Research

An overview of this research is provided in Figure 1. Five sections follow this introduction. A review of the theories of contextual technology answers three questions: What is the current state of research into the theories of discontinuous and disruptive innovation? How did each theory develop? What are the relevant variables? Following this literature review, a typology is constructed that integrates the theories of discontinuous and disruptive innovation. This typology forms the central hypothesis that this research proposes to test.

The next section describes the methodology of this research in detail. It describes the population of data that is mined and the sampling techniques that are employed. It examines the reliability and validity of the instruments used to measure the variables in the data sample. It also describes the procedures that are followed to construct the desired taxonomy and concludes with a discussion of the internal and external validity of this research.

Lastly, the final two sections of this dissertation present an analysis of the data collected and conclude by answering the questions that first framed this dissertation.

FIGURE 1
Research Approach Overview

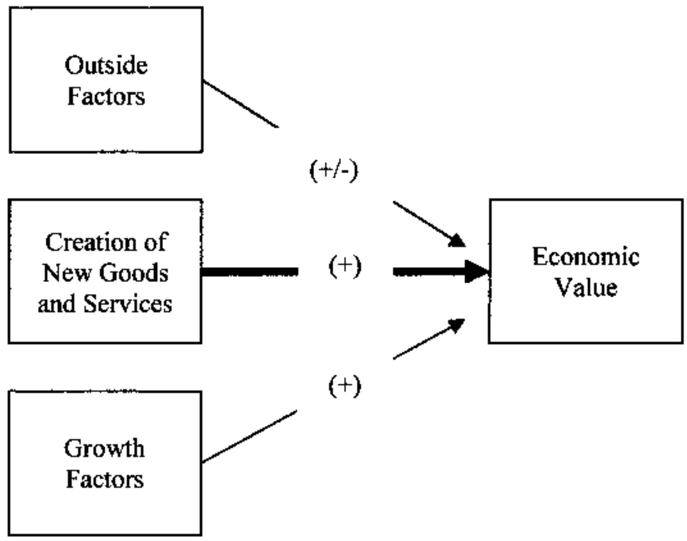


THEORIES OF CONTEXTUAL TECHNOLOGY

This section reviews several theories and their related typologies as they describe innovation from the perspective of contextual technology. It will be shown that these theories can be grouped according to the three dimensions of innovation that they attempt to explain: changes in component performance, markets, and system architecture. The theory of discontinuous innovation is a theory of core performance. The theory of disruptive innovation is a theory of markets and system architecture. Any typology that integrates the two theories must include all three dimensions. The next chapter examines a new typology – a hypothesis - that integrates these two theories. Overall, these two chapters answer the first two research questions (1 and 2) and prepare the way for a test of this dissertation's ability to reconcile the theories of discontinuous and disruptive innovation.

Schumpeter's concept of *creative destruction* is the foundation of most innovation research today (Scherer, 1992). In 1942, Schumpeter (1976) observed many of the improvements in our standard of living at the turn of the 20^{th} century and noted that big businesses drive our capitalist economy. He emphasized that capitalism is not a static equilibrium of economic transactions, but instead, a dynamic evolutionary process. Schumpeter acknowledged the complex environment within which our capitalist society operates. War, revolution, and other outside factors (e.g., natural catastrophe, weather, disease, changes in law) influence our economic activity (Clemence, 1951; Schumpeter, 1935). Non-cyclical changes in underlying variables (e.g., increases in population) consistently spur economic growth (Clemence, 1951; Schumpeter, 1935). Despite these

FIGURE 2
Schumpeter's Factors of Economic Development



two factors, the core activity of capitalism is to compete in the production of goods and services for economic consumption. Therefore, the greatest engine driving capitalism is the creation of new goods and services (Schumpeter, 1976) (See Figure 2).

Schumpeter's description of *creative destruction* challenged the economic views of his day:

> Innovation led not only to superior new goods and services; it simultaneously undermined the market position of firms committed to old ways of doing business. It destroyed old monopolies while creating new economic value. (Scherer, 1992: 1418)

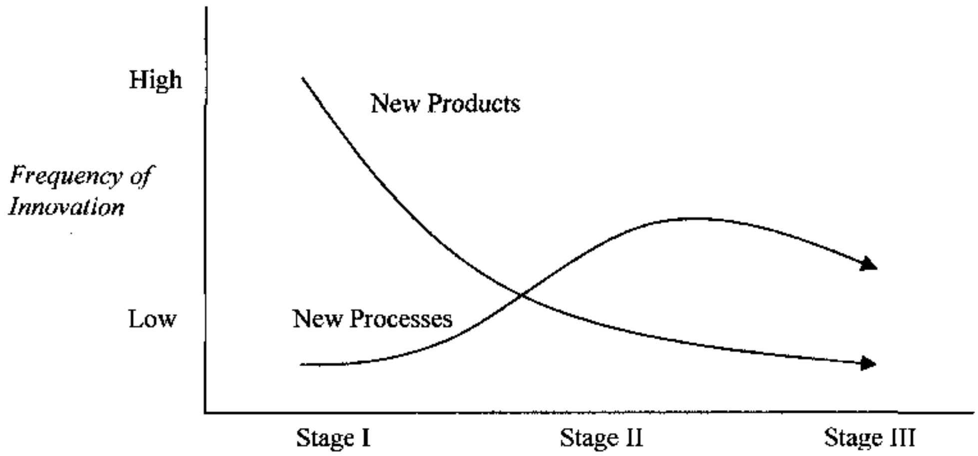
Schumpeter (1976) drew two conclusions. First, the effects of the creation of new goods and services are only revealed as time passes. Second, this model of economic change is an "organic process." Its constituent parts cannot be studied in isolation. As Schumpeter (1976: 83-84) states, "Every piece of business strategy acquires its true significance only against the background of the process and within the situation created by it."

Theories of Component Performance

Theories of component performance classify innovations according to the price and performance of a dominant attribute. Product innovations improve the performance of the dominant attribute through technological advances in the core components of the product. Process innovations reduce the cost of the product by improving the efficiency of the product delivery system. In these theories, radical innovation results in large changes in product or process performance. The theory of discontinuous innovation is a prominent member of the theories of component performance.

Abernathy & Townsend (1975) were among the first to characterize the development of industries as occurring in stages of process and product innovation. Utterback & Abernathy (1975) expanded on this development and created one of the earliest of the modern typologies with empirical evidence of linkages between a firm's competitive strategies, its production resources, and its ability to innovate. Utterback & Abernathy (1975) hypothesized that the competitive environment within which a firm operates strongly influences its competitive strategy. They model firm strategy as a dynamic process with three stages of development. In stage I, products are new to market and production processes are immature. This stage is characterized by a corporate strategy of maximizing product performance. In stage II, the market identifies key product characteristics and firms compete to maximize sales by differentiating their products. The manufacturing process becomes more specialized and focuses on making the process more efficient. In this second stage, corporate strategy focuses on maximizing sales. In stage III, the product design is fully defined as market and production factors become specialized to the point that improvements become expensive.

FIGURE 3
The Abernathy/Utterback Model of Innovation



Corporate strategy in this final stage is to minimize cost. Utterback & Abernathy (1975) combine these factors in a model of product and process development (Figure 3). This model is sometimes called the Technology Life Cycle model (DeBresson & Lampel, 1985a; Sood & Tellis, 2005) or the Industrial Development Model (Benkenstein & Bloch, 1993).

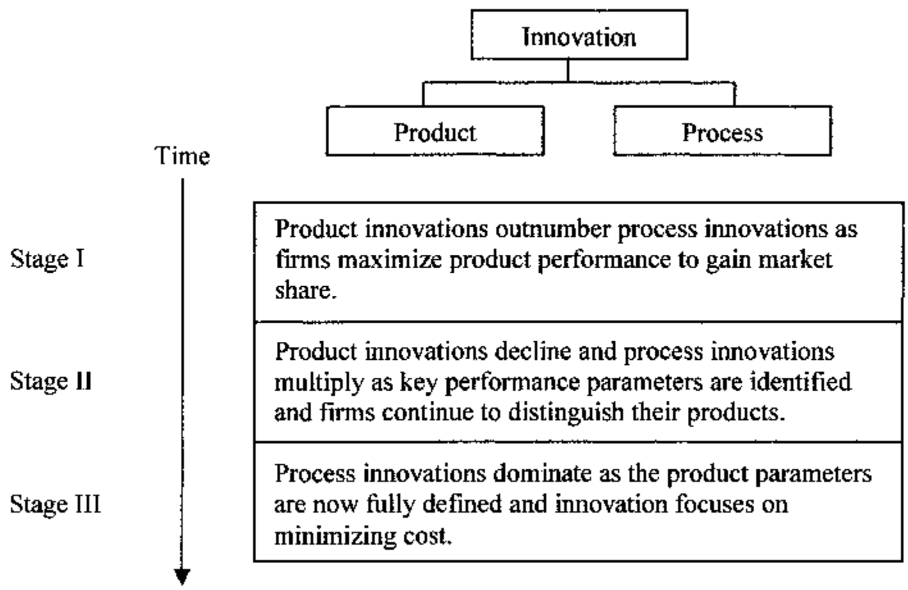
Utterback et al. (1975: 642) emphasized that innovation is a dynamic process, "The essential idea here is that a process, or productive segment, tends to evolve and change over time in a consistent and identifiable manner." This model also integrates environmental and technological factors. One criticism of the Abernathy/Utterback model points out that this model depicts innovation as a continuous

process. In reality, each innovation is a small disruption or change that carries with it opportunities for change (DeBresson et al., 1985a). As a result, the Abernathy/Utterback model is more descriptive of an industry and the dominant firms within that industry. It is does not represent the most likely path of every firm in the industry (DeBresson & Lampel, 1985b).

The Abernathy/Utterback model classifies innovations as either product or process. The interactions between products and processes are dependent upon the technological maturity of the industry (Stage I, II, and III). Time is an element in this model as the overall process is expected to move from Stage I through Stage III in sequence. The classification of innovations in the Abernathy/Utterback model is represented as a typology in Figure 4.

Abernathy & Utterback (1978) further classified innovations as either radical or incremental. While they granted that the gains from incremental innovation often eclipse the gains from the initial radical innovation (Enos, 1967; Hollander, 1965), the topic of radical innovation captured their focus. Extending their earlier model of dynamic innovation (Utterback et al., 1975), they concluded that radical innovations occur early in the product/firm lifecycle. They reasoned that small firms with flexible production processes and close ties to the needs of the marketplace are largely responsible for successful radical innovations. Technological and market uncertainty are key incentives that drive small firms and deter larger firms in the Stage I industry environment. As products mature, uncertainties about the technologies needed to produce the product and key product characteristics are reduced. Large firms now have incentive to invest in the research and development necessary to pursue innovations that will incrementally improve performance while driving down cost. In all of these arguments, technology alone does not drive the model; it is the interplay between technology, market needs, and the firm's production processes.

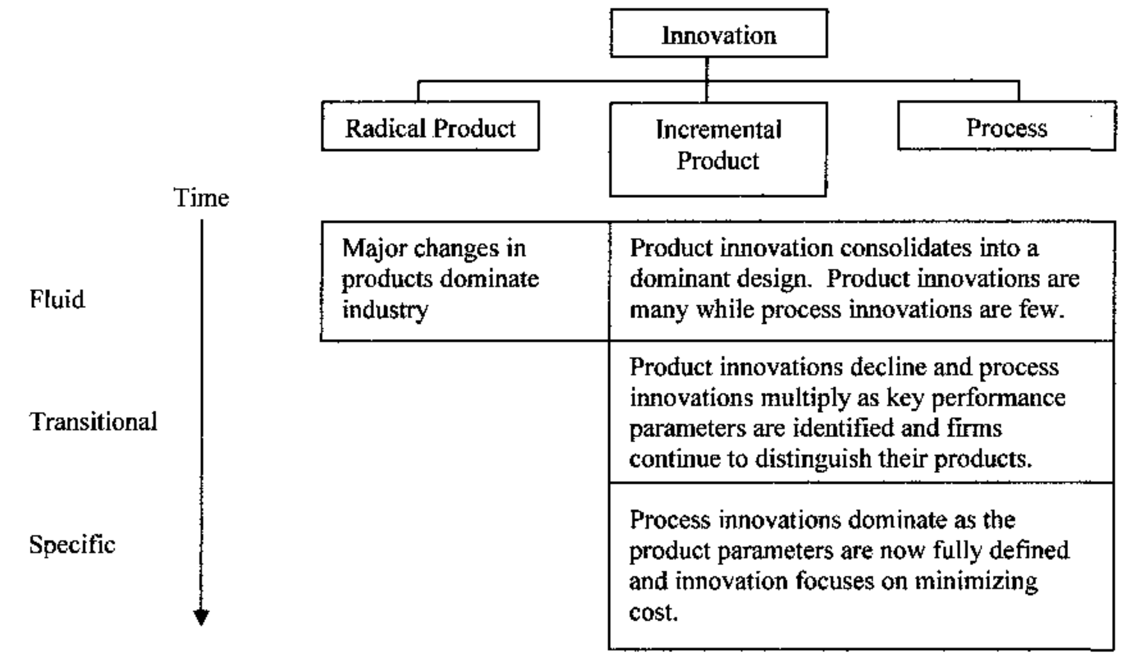
FIGURE 4
A Typology of the Abernathy/Utterback Model of Innovation



Abernathy (1978) expanded his model of innovation to include what he describes as a dominant design in his book, *The Productivity Dilemma.* The predominant mode of innovation shifts from product to process when a dominant design emerges. Once this shift occurs, improvements to the dominant design are achieved through incremental innovations. Abernathy (1978: 57) argued that a dominant design is not itself the result of a radical innovation, "To the contrary, a design approach becomes dominant …when the weight of many innovations tilts the economic balance in favor of one design approach." Unfortunately, dominant designs can only be identified once they have occurred (Gallagher, 2007).

In the theories discussed thus far, technology does not drive innovation as much as it enables it (Abernathy, 1978; Abernathy et al., 1975). Abernathy (1978) noted how the introduction of the metal, vanadium, into automobile manufacturing triggered the design of the Ford Model T. According to Abernathy (1978), the discovery of this relatively low cost, high strength alloy caused Henry Ford to embark upon a new business strategy that resulted in the development of the Model T. It was the strategy and not the metal that resulted in Ford's competitive success. Abernathy (1978: 170) noted, "Evidence from a variety of different viewpoints suggests that innovations do not frequently occur through a process wherein advanced technologies seek out new needs, but instead a new understanding about needs draws in the best available technology." The Abernathy/Utterback model is an important step in the development of our understanding of innovation. It synthesizes incremental and radical innovation into a model of product and processes innovation. It predicts that innovation is greatest when markets and firm factors are most uncertain. Productivity is enhanced by reducing market and production uncertainty. Therefore, innovation is inversely proportional to the productivity of the firm's production processes. The role of corporate strategy is to balance the competing demands for innovation and productivity. It also predicts that the likelihood of a radical innovation decreases as time advances. Abernathy (1978) caveats the deterministic nature of his model. While difficult to execute, strong environmental influences can reverse the process and demand a change in design. In the end, Abernathy (1978: 59) stated that, "because improvements are cumulative, the chance decreases with time that a single innovation will change a favored approach". Figure 5 depicts an updated typology of Utterback & Abernathy's (1978) model of innovation.

FIGURE 5
An Updated Typology of the Abernathy/Utterback Model of Innovation



DeBresson & Lampel (1985a) critiqued the assumptions behind the Abernathy/ Utterback model arguing that the model implies a deterministic progress through each stage in linear fashion. They felt that empirical evidence requires a less linear view of technology development with the ability to jump forwards or backwards as strategic circumstances dictate. Markets and competition may allow different stages to exist simultaneously. They also criticized the life-cycle model's weak treatment of technological discontinuities and radical innovations that resulted "from an accumulation of incremental changes and recombination of existing technologies" (DeBresson et al., 1985a: 174).

DeBresson & Lampel (1985a) emphasized that the Abernathy/Utterback model is more valuable at the industry level of analysis than at the firm level. They demonstrated that production processes (custom, batch, and line) influence interactions between product and process beyond what are predicted by the Abernathy/Utterback model. Most of all, they argued that managers must constantly assess whether continued incremental development along existing model lines is being threatened by radical innovation.

Adner & Levinthal (2001) examined the Abernathy/Utterback model through the lens of economic competition. They proposed that the assumptions of the Abernathy/ Utterback model do not sufficiently emphasize the importance of the maturing customer demand. They explained that customers establish a functionality threshold below which they will not consider purchasing a product and a net utility threshold that represents the maximum price that a customer is willing to pay for a product. Adner & Levinthal (2001) developed an economic model to study the interaction of product and process innovation on product performance and price. Their model produces three stages of development that do not directly correlate with the Abernathy/Utterback model. In the Adner/ Levinthal model, the first stage represents attribute equalization where either product or process innovation might dominate as industries respond to unmet market demands. The second stage, market expansion is dominated by process innovation as industries move to exploit their footholds in the market by lowering cost. The final stage, demand maturity, favors both product and process innovation as the prices stabilize and as firms in the industry pursue both product and process innovations in order to differentiate their offerings. Adner & Levinthal (2001: 627) concluded that,

> Viewing the evolution of technology through a demand-based lens suggests that the early evolution of technologies is guided by responding to the unsatisfied needs of the market. After sufficient development, however, firms face the intriguing possibility that these guiding needs have largely been satisfied. The framework developed here suggests that

> product maturity may be as much a function of satisfied needs as it is of exhausted technologies.

Tushman & Anderson (1986) focused on understanding the implications of technological discontinuities. As businesses interact within industries, they spur each other to make incremental changes that improve a product's performance or reduce product cost as they jockey for competitive position. Technological discontinuities occur when a great technological advance occurs and the industry no longer finds the previous group of technologies competitive (Tushman et al., 1986).

Tushman & Anderson (1986) investigated technological discontinuities within the cement, airlines, and microcomputer industries (Table 2). Their central assumption was that technological progress is evolutionary in nature,

> Case studies across a range of industries indicate that technological progress constitutes an evolutionary system punctuated by discontinuous change. Major product breakthroughs (e.g., jets or xerography) or process technological breakthroughs (e.g., float glass) are relatively rare and tend to be driven by individual genius. (Tushman et al., 1986: 440)

Technological advances, individual choices, and environmental conditions combine to produce an evolutionary view that industries follow the path of incremental innovation for relatively long, stable periods. However, the technological advances of products and processes are not always incremental. Industries are interrupted infrequently, but significantly, by discontinuous innovations (Tushman et al., 1986) in an echo of Schumpeter's description of creative destruction.

Technological discontinuities were further classified into either competence-enhancing or competence-destroying technological shifts (Tushman et al., 1986). Firms in industries undergoing competence-enhancing technological shifts find that they already possess the knowledge, skills, and ability to pursue the new technology.

TABLE 2
Technological Discontinuities in the Cement, Airline, and Minicomputer Industries (Adapted from Tushman & Anderson, 1986)

Cement Industry Barrel per Day production Capacity from 1890-1980

Year	Innovation	% Improvement	Impact on Firm Competence
1894	Rotary Kiln	310%	Destroying
1909	Edison Long Kiln	120%	Enhancing
1967	Dundee Kiln	190%	Enhancing

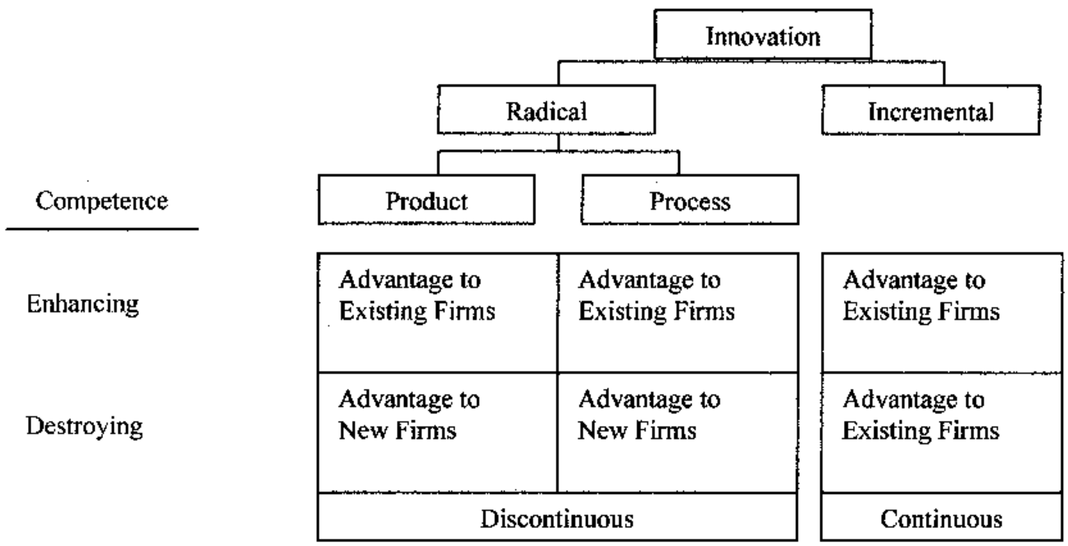
Airline Industry Seat-Miles per Year Capacity from 1930-1978

Year	Innovation	% Improvement	Impact on Firm Competence
1932-1936	Boeing 247, DC-2, DC-3	410%	Enhancing
1959	Boeing 707-120	250%	Enhancing
1969	Boeing 747	150%	Enhancing

Minicomputer Industry Central Processing Unit Cycle Time from 1956-

Year	Innovation	% Improvement	Impact on Firm Competence
1962	Pac Bell PB-250 (transistors)	1000%	Niche Opening
1964	DEC PDP-8 (Integrated Circuits)	750%	Destroying
1971	Data General Superdata SC (Semiconductor Memory)	200%	Enhancing

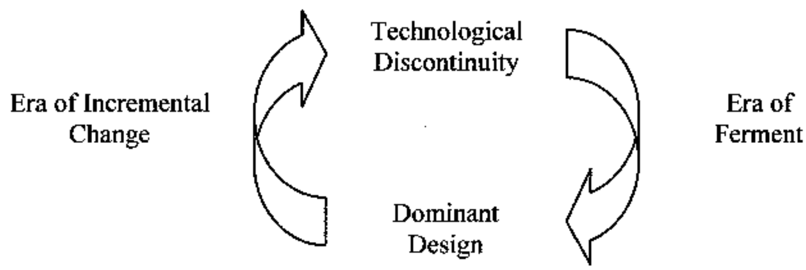
FIGURE 6
A Typology of Tushman & Anderson's (1986) Model of Discontinuous Innovation



The development of screw propellers for ships and fan jet engines for airplanes are examples of competence-enhancing innovations (Tushman et al., 1986). In each of these cases, aircraft manufacturers and shipyards were able to adapt existing knowledge, skills, and abilities to take advantage of the new technology.

Alternatively, in competence-destroying technological shifts, existing firms find they do not possess the knowledge, skills, and abilities to compete. Using examples such as the introduction of automobiles or the substitution of diesel locomotives for steam, Tushman & Anderson (1986) suggested that competence-destroying technological shifts will typically be introduced by new entrants to the industry and fundamentally alter the ability of existing firms to compete in the industry environment. As a result, many existing firms may not survive the transition. Tushman & Anderson's (1986) model for classification of discontinuous innovation is provided in Figure 6.

FIGURE 7
Anderson & Tushman's (1990) Technological Cycle



Four years later, Anderson & Tushman (1990) integrated their views on technological discontinuities into a model of a technological cycle. Drawing upon data from the glass container, flat glass, cement, and minicomputer industries, they demonstrated that there are two boundary events of concern in the progress of technological innovation. When technological discontinuities occur, they initiate an intense period of competition where industry firms adapt their products and process to find the combination of attributes (performance, quality, and cost) that customers prefer. This period of competition was labeled by Anderson & Tushman (1990) as the era of ferment. The era of ferment is terminated when customers select a dominant design. At this point, the focus of innovation shifts to incremental improvements in product attributes. This era was labeled the era of incremental change (see Figure 7).

Anderson & Tushman (1990) emphasized several characteristics of this technological cycle:

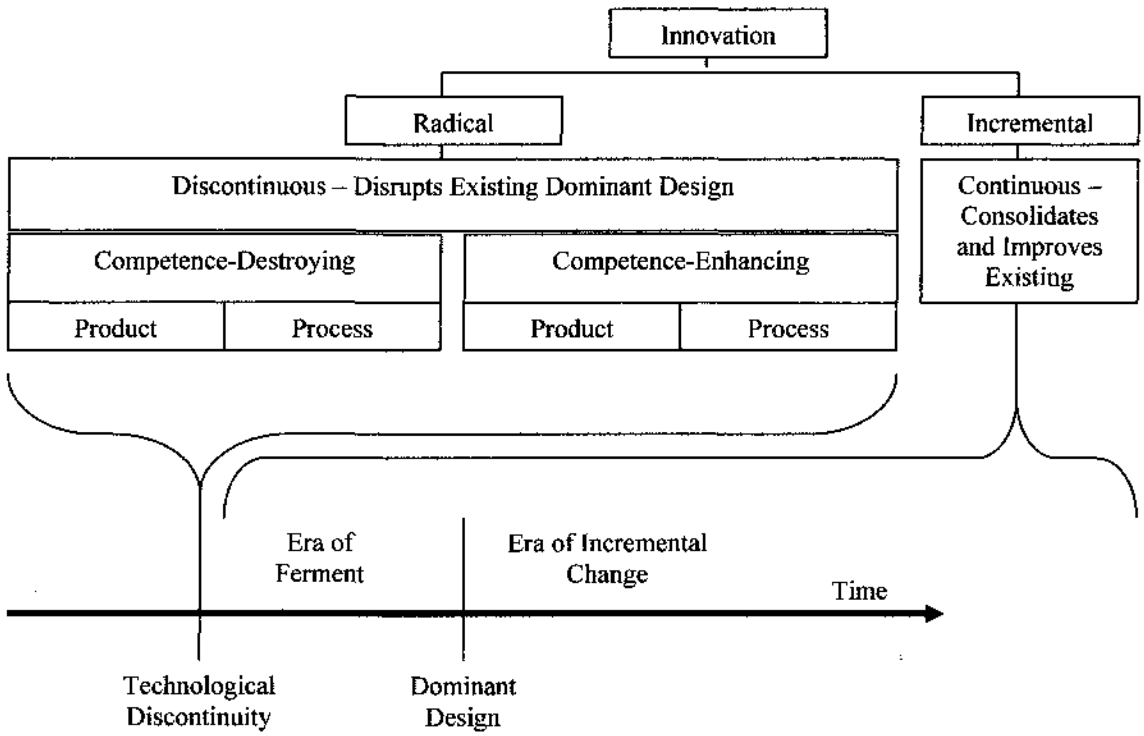
- Technological discontinuities usually result in a new dominant design unless there are market mechanisms (legal, statutory, etc.) in place that protect existing designs.

- Sales demand peaks following the emergence of the dominant designs implying that many customers wait for design stability before making their purchase.
- The technological discontinuity that begins the era of ferment rarely becomes the dominant design. The competition of designs in the era of ferment usually adapts or modifies the original discontinuity. Additionally, while the technological capacity of the dominant design absorbs most of the attributes improved by the technological discontinuity, it is usually more conservative than the most advanced technology at the time.
- While their earlier research (Tushman et al., 1986) found that new entrants are more likely to introduce competence-destroying discontinuities, they found that both new-entrants and existing firms contributed to the introduction of dominant designs indicating increased role for existing firms in the era of ferment
- On average, the combined effect of the technological discontinuity and the era of ferment accounted for approximately 80% of the technological advance for the industries studied. Eras of incremental change accounted for the remaining 20%.

A typology representing Anderson & Tushman's (1990) updated model of discontinuous innovation is presented in Figure 8.

Anderson & Tushman (1990) suggested that firms initiating a technological discontinuity often do not end up determining the dominant design because of the many

FIGURE 8
An Updated Typology of Anderson & Tushman's (1990) Model of Discontinuous Innovation



factors (social, political, consumer preference, etc.) that combine in the design selection process. In the case of a competence-destroying technological discontinuity, Anderson & Tushman (1990) expected new entrants to the industry to have an advantage in the ensuing competition. Instead, they found that both incumbent and new entrants were capable of fielding the resulting dominant design. This suggests that incumbents are able to exploit other strengths in their value chains while re-investing in the technical skills that new technologies demand (Anderson & Tushman, 1991).

TABLE 3
Complementary Assets (Adapted from Teece, 1986)

Core Assets	Complementary Assets
Technological Competence	Competitive Manufacturing
	Distribution
	Service
	Complementary Technologies

Teece (1986) explained that a firm's complementary assets, such as marketing, manufacturing, and after-sales service support, may influence a firm's ability to take advantage of a technological innovation (Table 3). Teece (1986) characterized complementary assets as either generic, specialized, or co-specialized. Generic complementary assets are those assets that do not need to be adapted to the innovation. Assets are specialized when there is a unilateral reliance of the innovation on the asset or the asset on the innovation. Assets are co-specialized when the assets and the innovation are co-dependent. For example, if the innovation is a new sneaker, manufacturing assets may be generic because the injection mold process can easily adapt to the innovation.

Teece (1986) used shipping containers to distinguish co-specialized from specialized assets. The containerization of shipping cargo is an innovation that is co-dependent upon specialized handling gear at ports and is dependent upon trucking for distribution out of ports. Trucks can be modified for various cargos – including containers – relatively easily. Therefore, the port assets are co-specialized assets and trucks are specialized assets with respect to the innovation of shipping containers. Teece

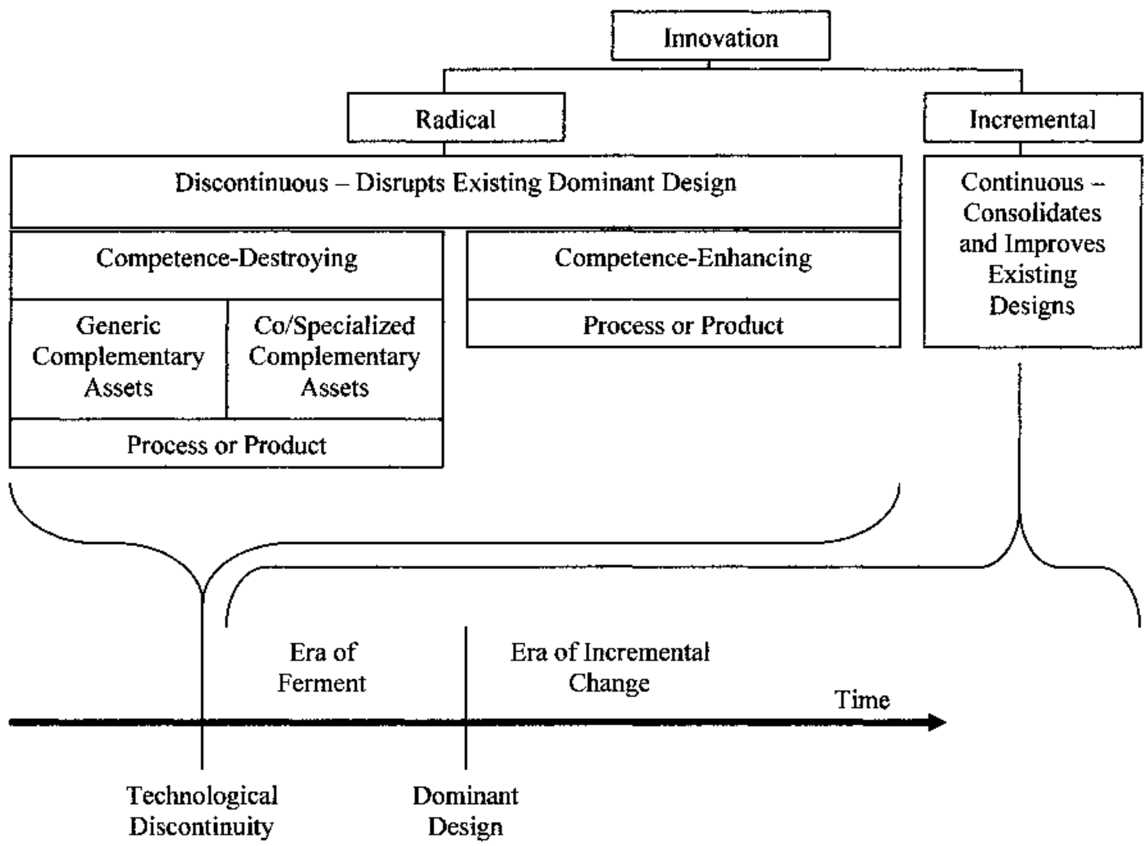
(1986) concluded that complementary assets will significantly affect which firms will profit from innovation.

Rothaermel & Hill (2005) examined the concept of complementary assets and incorporate their findings into Anderson & Tushman's (1990) model of discontinuous innovation. Examining data from the computer, steel, pharmaceutical, and telecommunications industry, they provided evidence that incumbent firms fare worse after a competence-destroying technological discontinuity when complementary assets are generic and fare better when complementary assets are specialized or co-specialized. Rothaermel & Hill's (2005) contribution to the typology of discontinuous innovation is shown in Figure 9.

Murmann & Frenken (2006) proposed a two dimensional typology in their research into dominant design. They categorized innovation along dimensions of performance and knowledge. Innovations with relatively small gains in performance and knowledge were classified as incremental. Innovations with significant performance gains but modest knowledge gains were classified as radical-performance sense. Innovations with significant knowledge requirements but modest performance gains were classified as radical-knowledge sense. Innovations with both performance and knowledge gains were classified radical squared.

In many ways, Murmann & Frenken's (2006) system of classification maps to the theory of discontinuous innovation (Tushman et al., 1986). Radical-performance sense might be equivalent to discontinuous competence-enhancing innovations. Radical squared innovations might then equate to discontinuous competence-destroying innovations. The remaining category, radical-knowledge sense, has no equivalent in the

FIGURE 9
An Updated Typology Following Rothearmel & Hill's (2005) Introduction of Complementary Assets into the Model of Discontinuous Innovation



theory of discontinuous innovation and is difficult to interpret since no underlying theory is presented for this typology.

The typologies and theories of component performance contribute to the practice of innovation management in many ways. The technology life-cycle suggests that managerial action should be compatible with the maturity of the technology within the industry (Abernathy et al., 1978) and the maturity of the market demand (Adner et al., 2001). Industry shakeouts are triggered more by technological change than by economic downturns (Anderson et al., 1991). Technological discontinuities and unpredictable market demand combine to create uncertainty for technology managers (Anderson et al., 2001) and firm survival is strongly influenced by the firm's technological competence (Tushman et al., 1986) and complementary assets (Rothaermel et al., 2005).

These theories have been used to evaluate managerial tools for project evaluation (Benkenstein et al., 1993); assess the impact of strategic alliances (Rothaermel, 2002) and managerial recognition of the discontinuity (Kaplan, Murray, & Henderson, 2003) on firm success; and interpret national level policies during periods of ferment (Dalum, Pedersen, & Villumsen, 2005). The primary limitation of these studies is noted by Anderson (1988: 197) , "Almost all longitudinal studies suffer from the twin problems of a small sample size and limited generalizability."

In summary, there have been two major theoretical typologies that emerge from the theories of component performance. First, there is the technology development cycle, defined by Utterback & Abernathy (1975), where product and process innovations are modeled against a maturing technology. Radical innovations are seen primarily as the technological advances that launch the development cycle. Second, there is the theory of discontinuous innovation where a more holistic view of technology development is proposed (Tushman et al., 1986).

The theory of discontinuous innovation suggests that industries are periodically disturbed by technological developments that cause fundamental changes in the products or processes. These disturbances, or discontinuities, are followed by an era of ferment where firms compete to adapt to the new technology and create a new design for the industry. Once a dominant design emerges, competition shifts to incremental development as firms adopt the dominant design and compete for their share of the market. The development of the typologies of component performance is summarized in Table 4.

Theories of Component Performance and Markets

Theories of component performance and markets explore interactions between customer preferences in the market and the technological development of components to classify innovations. The technological dimension of these theories retains the sense of determinism, the relentless march of scientific progress expressed in Anderson & Tushman's (1990) technological cycles. The market dimension, however, begins to introduce a more capricious variable to the innovation equation. For these researchers, industry changes introduced by innovations that shift customers' perceptions of product quality or performance are categorized along with innovations in component performance.

Ansoff (1965) created an early typology of corporate growth by mapping the development of new products to the needs of the market (See Figure 10). The purpose of this typology was to develop categories of corporate growth that would better describe the strategic choices of the firm. The appropriate strategy for growth with existing products in existing markets is to increase market share or market penetration. Strategies that pursue new products or new markets with existing products are categorized as product development and market development respectively. Ansoff (1965) felt that a corporate strategy of diversification that pursued both new products and new markets provided a weaker link to corporate strategy because it required both new marketing skills and new product technology. Given the obvious linkages between corporate

TABLE 4
Typologies of Component Performance

Reference	Type of Innovation	Variables	Categories Specified
Abernathy & Townsend, 1975	Product and Process	Technological innovation Process Improvement	1. Uncoordinated 2. Segmental 3. Systemic
Utterback & Abernathy, 1975	Product and Process	Product Innovation Process Innovation Time	1. Stage I: Uncoordinated Process 2. Stage II: Segmental Process 3. Stage III: Systemic Process
Abernathy & Utterback, 1978	Product and Process	Rate of Innovation Technology Maturity	1. Fluid 2. Transitional 3. Specific
Tushman & Anderson, 1986	Discontinuous Product and Process	Radicalness Firm Competencies Product vs. Process	1. Incremental 2. Discontinuous competence-enhancing 3. Discontinuous competence-destroying
Anderson & Tushman, 1990	Discontinuous Product and Process	Technological Discontinuity Dominant Design	1. Era of Ferment 2. Era of Incremental Design
Adner & Levinthal, 2001	Product and Process	Functional thresholds Net Utility thresholds Product vs. Process	1. Attribute Equalization 2. Market Penetration 3. Demand Maturity
Rothaermel & Hill, 2005	Discontinuous Product and Process	Radicalness Upstream competencies Complementary assets	1. Incremental 2. Discontinuous competence-enhancing 3. Discontinuous competence-destroying & generic 4. Discontinuous competence-destroying & co/ specialized
Murmann & Frenken, 2006	Incremental and Radical	Technology performance New Knowledge	1. Incremental 2. Radical-Performance Sense 3. Radical – Knowledge Sense 4. Radical Squared

FIGURE 10
Ansoff's (1965) Growth Matrix

	Present Product	New Product
Present Market Need	Market Penetration	Product Development
New Market Need	Market Development	Diversification

growth, new product development, and innovation, Ansoff's matrix is an early and important foundation to the typologies of component performance and markets.

Abernathy & Clark (1985) explored innovation from the perspective of its relationship with firm competencies. The purpose of their research was to create a framework for categorizing innovation from a perspective of understanding the role of innovation in the competitive environment. Their hope was that corporate strategy would be better informed by understanding the impact of market context on technological progress.

In considering the effects of innovation on firms, they defined a concept they called "transilience" – an innovation's "capacity to influence a firm's existing resources, skills, and knowledge" (Abernathy et al., 1985: 5). They developed a scale that measured an innovation's impact on a firm's knowledge in both the market and technology dimensions. For example, some innovations rely on a firm's knowledge of existing

FIGURE 11
The Typology of Transilience (Adapted from Abernathy & Clark, 1985)

Requires New Market Competency	Niche Creation	Architectural
Uses Existing Market Competency	Regular	Revolutionary
	Uses Existing Technological Competency	Requires New Technological Competency

markets while others require knowledge of new markets. A similar scale was constructed to measure the impact of innovation on a firm's technical knowledge. By measuring innovations from the U.S. auto industry against these two variables, firm market and technological competencies, they provided examples of four different types of innovation.

Abernathy & Clark (1985) described innovations that synthesize new technical capabilities with new markets as architectural - innovations that whole industries can be built upon. Innovations that use existing technology to exploit new markets are categorized as niche innovations. These are innovations that may gain temporary advantage by leading an industry but can be easily copied by competing firms. Innovations that employ new technologies in existing markets are categorized as revolutionary, and innovations that incrementally improve existing technologies in existing markets are categorized as regular (See Figure 11). Danneels (2002) employed a similar typology in his later research into the impact of product innovation on organizational renewal, albeit with different category labels. Veryzer (1998) mapped the technological advance of component performance against the perceptions of customers regarding product novelty. Small changes are labeled continuous, and radical changes are discontinuous. Veryzer (1998) used the term "discontinuous" less in the specific sense of a quantitative discontinuity in a product technology curve (Tushman et al., 1986) and more as other researchers use radical vs. incremental.

Veryzer's typology does not map directly to a larger theory of innovation. It suggests that customer perceptions of product performance are equally important in the categorization of innovation. Products with little novelty either in technology or customer perception of product capability are categorized as continuous innovations. If the technology change is small but the perceived product capability is significant, the innovation is categorized as commercially discontinuous. The innovation is categorized as technologically discontinuous if the technological change is significant and the customer perception of change is minor. The final category is for a product that is both technologically and commercially discontinuous (Figure 12).

Chandy & Tellis' (1998) typology echoes the logic of Ansoff's matrix in its classification of innovation according to technological advance and customer need. However, Chandy & Tellis (1998: 475) defined radical product innovation as "new products that (1) incorporate substantially different technology from existing products and (2) can fulfill key customer needs better than existing products."

FIGURE 12
Veryzer's Typology of Product Innovation (Adapted from Veryzer, 1998)

	Same Product Capability	Enhanced Product Capability
Same Technological Capability	Continuous	Commercially Discontinuous
Advanced Technological Capability	Technologically Discontinuous	Technologically and Commercially Discontinuous

Where Ansoff (1965) looked to fulfill new customer needs, Chandy & Tellis (1998) looked to fulfill existing needs better. Additionally, Chandy & Tellis (1998) introduced a financial component into the typology. They measured not the fulfillment of customer need, but the fulfillment of customer need per dollar.

Chandy & Tellis (1998) used their matrix to identify a link between managers in highly competitive industries (computer hardware, photonics, and telecommunications) who reported having introduced radical product innovations and the willingness of these managers to cannibalize existing resources and technologies. Their typology is largely self-explanatory and similar to others examined earlier (See Figure 13) in that it creates four categories (incremental, technological breakthrough, market breakthrough, and radical innovation) as the products of technological advance and fulfillment of customer need per dollar. Herrman, Tomczak, & Befurt (2006) extended the research of Chandy & Tellis (1998) in their research into the determinants of radical product innovation

FIGURE 13
Chandy & Tellis (1998) Typology of Product Innovation

	Low Customer Need Fulfillment per Dollar	High Customer Need Fulfillment per Dollar
Low Newness of Technology	Incremental	Market Breakthrough
High Newness of Technology	Technological Breakthrough	Radical Innovation

although, again, the labels of each category change and the customer need per dollar variable is simplified to customer need.

Danneels (2002) constructed a now familiar 2x2 matrix typology by distinguishing the competencies required to develop technology from the competencies used by organizations to serve customers. Product innovations that utilize existing technological and customer competencies are labeled exploitative. Product innovations that utilize new technological or new customer knowledge or skills are labeled as leveraging technological or customer competencies respectively. Innovative products that require new technological and customer competencies are labeled explorative. Danneels (2002: 1105) argued that a competency-based typology "provides a better understanding of the nature of various types of product innovations, their various challenges and requirements, and their implications for firm renewal."

Herrmann et al. (2006) distinguished radical innovations based upon their technological and market novelty. Innovations that use existing technologies and are familiar to customers are labeled incremental. When new technologies are introduced that are transparent to customers, innovations are labeled as company-related product innovations. When existing technologies are combined to produce new customer value, the innovation is labeled as customer-related product innovation. Radical innovations introduce both novel technologies and novel utility from the perspective of the customer.

The typologies of component performance and markets continue the theme that managers should take contextual factors into account in their pursuit of innovation (Abernathy et al., 1985). Innovative skill requires more than the ability to use new technology to improve the performance of products. It also requires understanding of the importance of customer perceptions (Veryzer, 1998), customer needs (Chandy et al., 1998; Herrmann et al., 2006) and firm competence in new and existing markets (Abernathy et al., 1985; Danneels, 2002). As a result, different types of innovation may require different managerial processes (Danneels, 2002).

Research founded on these typologies reinforces the idea that management of a firm's technical skills is central to innovative success (Gatignon & Xuereb, 1997; Mitchell & Singh, 1993). Managers that successfully expand their firms into new technical sub fields survive longer and achieve greater market share (Mitchell et al., 1993). In highly competitive markets with clear market signals, incremental strategies that focus on differentiating their product from their competitors and minimize the costs associated with innovation fare better (Gatignon et al., 1997). When market demand becomes less certain and customer perceptions of value and need are more variable, firm strategies emphasizing the customer and technological competencies are more successful (Gatignon et al., 1997). While a willingness to cannibalize firm resources may be necessary to introduce radical innovations (Chandy et al., 1998; Herrmann et al., 2006), few firms introduce radical innovations (Sorescu et al., 2003) and even fewer firms are persistently innovative (Geroski, Van Reenen, & Walters, 1997). In general, firms with greater per product marketing and technological capacity receive greater returns on their innovations investment (Sorescu et al., 2003).

Unlike the typologies that focused solely on component performance, these typologies do not explore the interplay of process and product innovation. Additionally, these typologies have not spurred theoretical models as widely used as the technology life cycle (Utterback et al., 1975) and the cycles of discontinuous innovation (Anderson et al., 1990). A summary of the typologies of component performance and markets is provided in Table 5.

Theories of Component Performance and System Architecture

When researchers began to look at the product itself as a system (Henderson et al., 1990), a new dimension in radical innovation was revealed. Early research into the systems views of innovation supports the typologies of component performance and focuses on the more holistic view of the innovation within the organization and its environment (Normann, 1971; Rosenbloom, 1978; Sahal, 1981). Appreciation of the product as a system also contributed significantly to the birth of the theory of disruptive innovation (Christensen, 1992b).

TABLE 5
Typologies of Component Performance and Markets

Reference	Type of Innovation	Variables	Categories Specified
Ansoff, 1965	Product	Product Newness Market Need	1. Market penetration 2. Market Development 3. Product Development 4. Diversification
Abernathy & Clark, 1985	Product	Technological Competence Market Competence	1. Regular 2. Niche Creation 3. Revolutionary 4. Architectural
Veryzer, 1998	Product	Technological Capability Product Capability	1. Continuous 2. Commercially Discontinuous 3. Technologically Discontinuous 4. Commercially and Technologically Discontinuous
Chandy & Tellis, 1998	Product	Technological Newness Customer Need per Dollar	1. Incremental 2. Market Breakthrough 3. Technological Breakthrough 4. Radical Innovation
Danneels, 2002	Product	Technological Competence Market Competence	1. Exploitative 2. Leveraging Technological Competence 3. Leveraging Customer Competence 4. Explorative
Herrmann et al, 2006	Product	Technological newness Market newness	1. Incremental 2. Customer Related 3. Company Related 4. Radical

Normann (1971) studied the relationships between organizational sub-systems and new product development. He viewed the product as a relationship between the firm and it's environment. Innovation is the process that manages changes in this relationship. Managerial action should be guided by a sense of "consonance" between new products and their environment:

> Consonance is a state of correspondence or mapping relationships between environment, product, and organization. Thus the product dimensions should correspond to the needs and values in the environment, while the specialized tasks of the organization must correspond to the product dimensions. Lack of correspondence will result in inefficiency. (Normann, 1971: 204)

Rosenbloom (1978) also viewed the firm as an open system interacting with its environment. He noted that while many empirical studies have been conducted looking at specific innovations, they lacked an "integrative theory" that might explain important relationships with a few key variables. Rosenbloom (1978) argued that a more integrative view might be developed at a higher level of abstraction by studying industries and firms. He stated that firms must take into account both external and internal influences in considering a strategy of technological innovation. He found that the innovation process, the firm's organizational structure, and the external environment all interact to result in a technological innovation.

Sahal (1981) established four systems principles that govern the general process of technological innovation:

- **The Principle of Technical Guideposts.** "…the process of innovation invariably leads to a certain pattern of machine design" (Sahal, 1981: 309) These guideposts become the basic design which incremental innovations improve over time. They tend to emerge as a synthesis of "proven concepts from the past" (Sahal, 1981: 309) and the more adaptable the design is to the task environment, the greater the potential advance of subsequent innovations. Finally, Sahal notes that the process of technological innovation is evolutionary and that "evolutionary processes tend to be both self-generating and self-constraining" (Sahal, 1981: 310). This principle tends to guide the short-term evolution of the process of innovation.

- **The Principle of Creative Symbiosis.** The evolution of a dominant design tends to result in a fixed form with increasing complexity. Creative symbiosis occurs when two or more designs recombine in such a way that the greater system is simplified redefining the guidepost and opening the door to further development. This principle tends to guide the long-term evolution of the process under study.
- **The Putty-Clay Principle**. Technical know-how tends to be task or object specific. As a result, while know-how is putty-like looking forward, it tends to harden like clay in hindsight. This principle highlights the difficulty of acquiring relevant know-how and the extent to which know-how tunes out to be system/design specific.
- **The Principle of Technological Insularity**. It is inherently difficult to transfer technical know-how. This is closely related to the putty-clay principle. "…Unlike pure scientific knowledge, which is equally available to all, technical know-how is largely product and plant specific." (Sahal, 1981: 59)

Henderson & Clark's (1990) typology of component performance and system architecture is borne out of research into case studies of innovation that are categorized as incremental innovations yet have great influence on the financial fortunes of leading firms in the industry. They examined the photolithography industry and found four examples where incremental technical changes – minor changes in component performance – combined with significant changes in relationships between the components, resulting in a change of leadership in the field. Henderson & Clark (1990: 16) postulated that this occurs because architectural knowledge is distinct from component knowledge:

> Since architectural knowledge is stable once a dominant design has been accepted, it can be encoded in these forms and thus becomes implicit. Organizations that are actively engaged in incremental innovation, which occurs within the context of stable architectural knowledge, are thus likely to manage much of their architectural knowledge implicitly by embedding it in their communication channels, information filters, and problem-solving strategies. Component knowledge, in contrast, is more likely to be managed explicitly because it is a constant source of incremental innovation.

Henderson & Clark's (1990) typology maps the development of core technology changes against architectural changes (See Figure 14). In this typology, incremental innovation is coupled with stable product architectures. Radical innovation is characterized by significant changes in both component technology and product architecture. Henderson & Clark (1990) present two new innovation categories to the field of innovation research - modular and architectural innovation. Modular innovation occurs when core technologies change but the product architecture remains unchanged. The transition from analog to digital telephones is an example of modular innovation. Architectural innovation occurs when the component technologies remain relatively the

FIGURE 14
Henderson & Clark (1990) Typology of Component versus System Innovation

Unchanged Relationship Between Components	Incremental Innovation	Modular Innovation
New Relationship Between Components	Architectural Innovation	Radical Innovation
	Core Technology Reinforced	Core Technology Overturned

same (minor changes may occur but the key knowledge remains unchanged) while the relationship between the components is changed. According to Henderson & Clark (1990), the introduction of portable fans would be viewed as an architectural innovation over existing ceiling fans. The fans have similar component technologies (fan blade, motor, housing units), but the size and configuration of the product is greatly different.

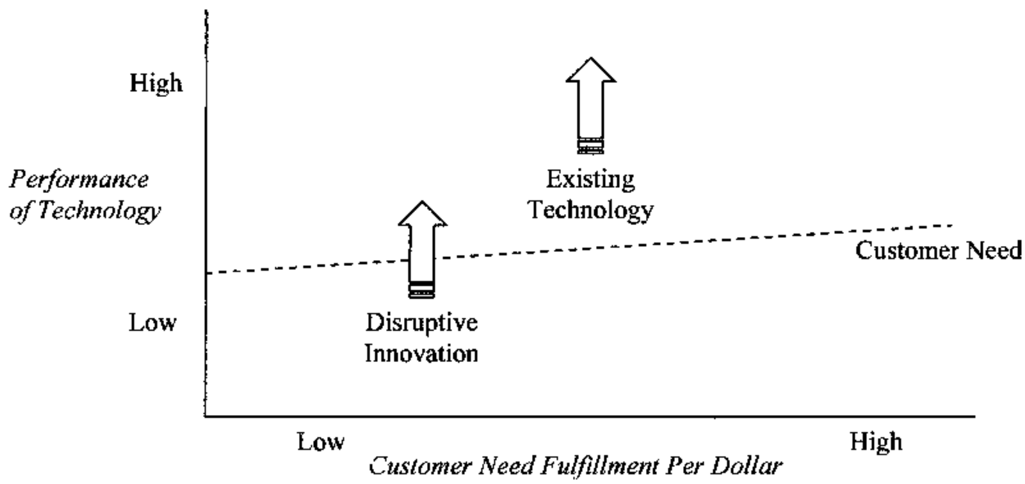
Theories of System Architecture and Markets

Christensen (1992b) applied Henderson & Clark's (1990) definition of architectural innovation to the industry turmoil he observed in the hard disk drive industry. Christensen (1992b; 1993) documented five waves of architectural innovations and the resulting shifts in industry leadership – as measured by market share – between 1973 and 1989. In each case, the size of the components shrunk and relationships between components changed as architectural designs were altered. Time and again, new entrants captured significant market share from incumbent market leaders by introducing new architectures to the market. Christensen (1992, 1993) confirmed that incumbent industry leaders retained competence in the core technologies throughout these transitions. When incumbents introduced the new architectures, the technical parameters of hard drives produced by incumbents were on par with the hard drives produced by new entrants that introduced the new architecture. In fact, Christensen (1992, 1993) documented several instances where the research teams of incumbents invented the new architecture. Yet, incumbent firms struggled to market the innovation until forced by competitive demands of the market. Christensen (1993) noted that the technology life cycle model did not explain the waves of innovation he observed:

> Generalizations that radically new technologies tend to be brought into industries by entrant firms; that established firms will excel primarily at the types of innovation that build on established technological competencies; or that established firms lead in component-level innovation because of their relatively greater ability to countenance greater complexity, risk, and expense seem to be inaccurate and insufficient to explain these patterns of innovation in the disk drive industry. (Christensen, 1993: 553)

Christensen (1997) explained this pattern in his well-known book, *The Innovator's Dilemma*. Disruptive innovations (Christensen, 1997; Christensen, Anthony, & Roth, 2004) change the market structure of an industry, displacing the knowledge and investments of mature incumbent businesses without requiring a radical advance in technology. As a new, potentially disruptive innovation emerges, it appears unattractive to incumbent businesses in the industry. Its technical performance is inferior to existing designs and its profit potential from the perspective of the incumbent business is too limited to pursue. Instead, entrepreneurs begin to employ this new technology in small markets of little interest to incumbents. Once established, these entrepreneurs have great incentive to develop their new technology to its fullest advantage.

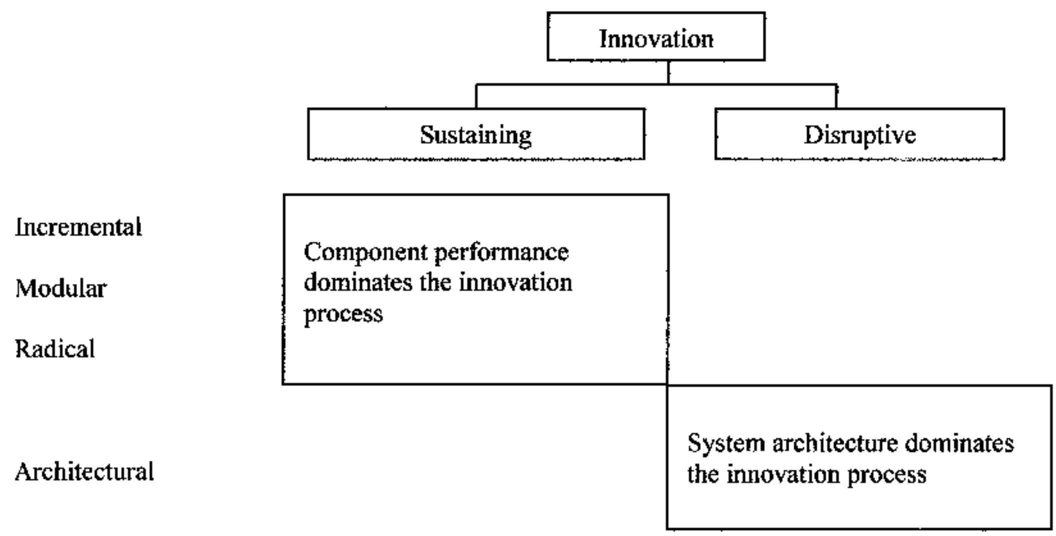
FIGURE 15
Low-End Disruptive Innovation (adapted from Christensen, Anthony & Roth, 2004)



Time passes and incumbent businesses find that the process of incremental innovation has caused the technical performance of these niche innovations to exceed the demands of the average customer, often with additional competitive value added such as reduced cost or improved convenience. At this point, incumbent companies become vulnerable to disruption. They find it difficult to compete with the new innovations and customers flock to the entrepreneurs in search of increased value as the disruption occurs (See Figure 15).

According to Christensen's (1997) theory (See Figure 16), disruptive innovations offer worse product performance than sustaining innovations. Sustaining innovations improve product performance. These advances may be either incremental or discontinuous. Disruptive innovations satisfy minimum customer needs while presenting a change in product design that is valued by the market. "Products based upon disruptive

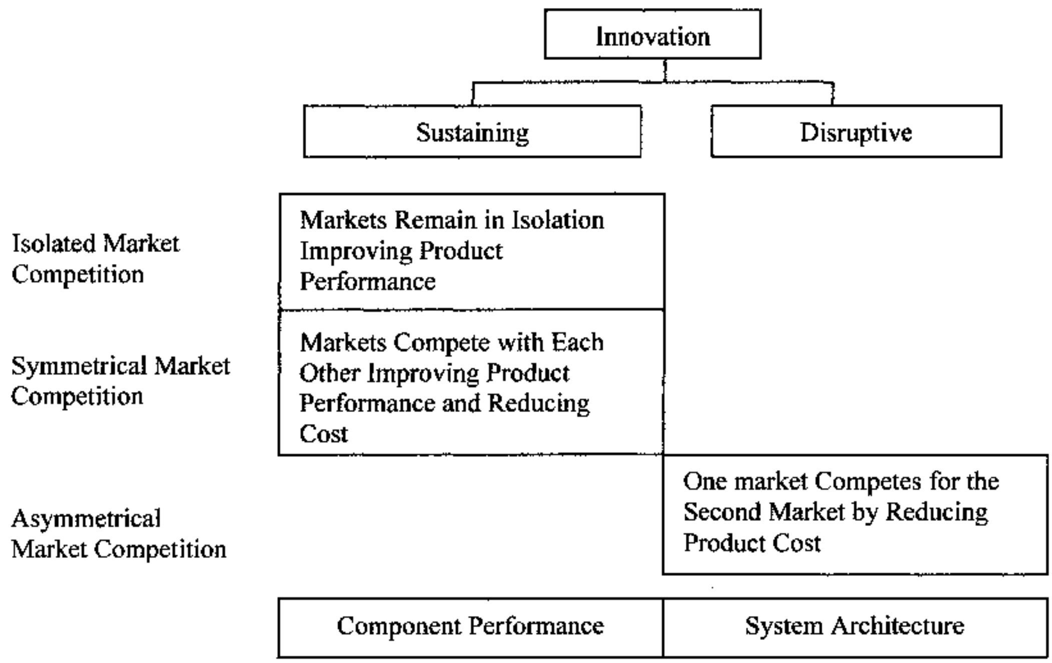
FIGURE 16
Christensen's (1997) Early Typology of Innovation



technologies are typically cheaper, simpler, smaller, and, frequently, more convenient to use" (Christensen, 1997: xv).

Adner (2002) explained how customer needs and price might explain the disruptive phenomenon. He showed that markets can be defined by the functional benefits that they offer to customers. When two markets are present, one of three competitive situations may arise. First, there may be no competitive overlap between to the two market and they may continue to develop in isolation. Second, each market may be motivated to compete in the opposing market. In this case, the competition is likely to be marked by increasing product performance and decreasing product cost. Lastly, one market may be asymmetrically motivated to compete in the second market. In this case, the satisfied market continues to drive up performance while the asymmetrically

FIGURE 17
Disruptive Typology Updated with Adner's (2002) Model of Economic Behavior



motivated market drives down cost. This third example is suggestive of disruptive innovation.

Adner's (2002) model of asymmetric competition modifies Christensen's theory (Figure 17). Christensen (1997) postulated that new attributes such as size and convenience drive market behavior once performance needs are met. Adner's (2002) model shows that cost plays a strong role in the disruption. When two competing products cost the same, customers are likely to choose the product with the best performance as long as the customer's functional utility threshold is met. However, if the disruptive product exceeds the functional utility threshold of customer at a lower cost, then it will be preferred over existing products even if they possess superior performance.

Christensen & Raynor (2003) updated the theory of disruptive innovation to included situations where new system architectures competed in a new market rather than in a low-end niche of existing markets. The mechanism of disruption remains the same. Rather than competing in the same market, the disruptive innovation competes from a different market. When asymmetric motivation (Adner, 2002) is present, the disruptive technology improves until its functional utility exceeds the demands of customer in the existing market. When this happens, customers adopt the disruptive innovation often at a reduced cost. Christensen & Raynor (2003) labeled this form of disruption as new market disruption.

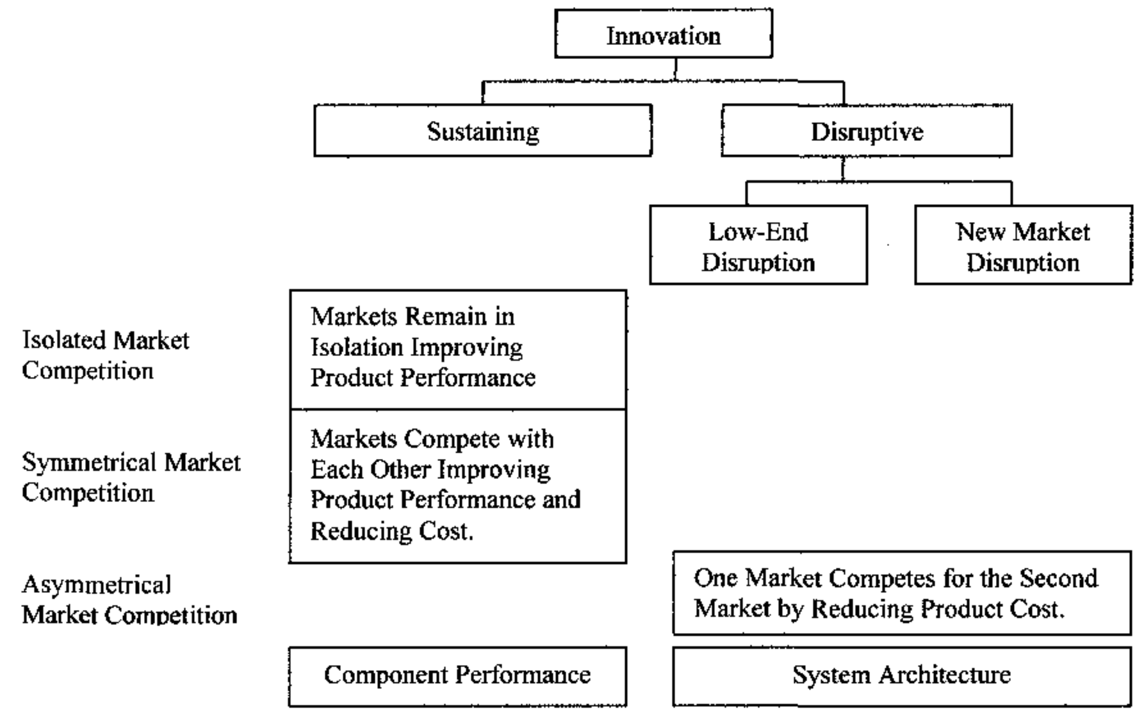
Markides (2006) disagreed with Christensen and argued that disruptive technological innovations should be distinguished from disruptive business models that uses existing technologies. Disruptive business models such as Internet banking and low cost airlines tend to capture a limited market share while disruptive technological innovations tend to dominate markets. Additionally, while existing firms are urged to form separate business units to pursue disruptive innovations (Christensen et al., 2003a), firms have many ways to adapt to disruptive business models (Markides, 2006). Markides (2006) also introduced the concept of a new-to the-world product as an innovation that does not fit into the existing models of disruptive innovation. New-to-the-world products (cars, computers, etc.) have great disruptive effects as radical innovations to both businesses and customers. Christensen (2006) agreed that the new-to-the-world category deserves study, but declined to categorize it as a form of disruptive theory.

Govindarajan & Kopalle (2006) introduced the concept of a high-end disruption. They found that a significant innovation in technology may create a new product that is inferior in terms of the attributes valued by mainstream customers but significantly better in others. The initial market for the high-end disruption is small and the cost is high, but continuing advances in technology bring the price of the product down and the mainstream market is invaded from above. The cellular telephone is provided as an example. However, Christensen (2006) explained that just because one technology supplants another emphasizing new attributes it is not automatically disruptive. The disruptive model requires a disruptive business model relative to the existing dominant design. Figure 18 shows the current forms of the typology of disruptive innovation.

The theory of disruptive innovation has been the subject of much debate (Danneels, 2004; Tellis, 2006) but Christensen provides convincing evidence of the strength of the disruptive model (Christensen, 2006). He emphasized that disruption is a relative effect. The company that introduces an architectural innovation into a low-end market niche follows a path of sustaining innovation in order to compete with mainstream market products. This same product continues to appear disruptive from the perspective of existing mainstream market firms. Additionally, Christensen (2006) argued that disruptiveness is not inherent in the product. Disruptiveness is a process and a business strategy. Disruption occurs as a result of the interactions between product attributes, customer needs, and the asymmetric motivation of market segments.

The theory of disruptive innovation has been applied in a wide variety of industries and situations. Disruptive theory has been used to assess the impact of tax incentives on innovation (White, 2001); guide investment decisions (Anthony & Christensen, 2005); assess the radiology profession (Chan, 2006) , the banking industry

FIGURE 18
Current Typology of Disruptive Innovation



(Albrecht, Andreas, Tawfik, & Harald, 2006), the education profession (Christensen, Aaron, & Clark, 2003b) and even macroeconomic policy in foreign affairs (Christensen, Craig, & Hart, 2001; Hart & Christensen, 2002) – to name just a few.

Christensen, Anthony, & Roth (2004) provided the following prescriptions for managers in the application of disruptive theory:

- Begin with an analysis of the marketplace. What are customer needs and have they been met or exceeded? What business models are in place? Are any new models emerging?
- Evaluate the competition from the perspective of Adner's (2002) models of competition. What symmetric and asymmetric motivations are in place?

- Make strategic choices in line with your firm's abilities and motivations. If a disruptive model is chosen, evaluate the need to spin out an independent organization in order to compete against existing markets.

Integrating Theories of Contextual Technology

Innovation researchers confuse fundamental concepts (Gatignon et al., 2002) and do not use consistent definitions or measures of innovation (Ehrnberg, 1995). For example, one research team defines discontinuous innovation as "major changes or innovations in basic products or services or programs offered or markets served, of the creation of new major product/service programs leading to new or expansion of current markets" (DeTienne & Koberg, 2002: 353). As a result, this researcher found that discontinuous innovation occurred often in a three year period. This directly contradicts the research of Anderson and Tushman (1986) who found that large technological advances, which they associated with discontinuous innovation, occur only rarely.

The research of Gatignon et al. (2002) suggests that innovations are best described by product complexity, locus of innovation, innovation type, and innovation characteristics. They adopted a systems-architectural view of innovation in that products are more or less complex. Products are composed of core subsystems tightly linked together with peripheral subsystems less tightly linked to product function. The locus of innovation occurs either within the core subsystem or in peripheral subsystems. Gatignon et al. (2002) characterized innovation types as either generational or architectural. Generational innovation changes subsystems while leaving the linkages between subsystems intact. Architectural innovation changes the linkages while leaving the subsystem intact. Discontinuous innovation would be considered generational. The disruptive innovation described by Christensen (1993) in the disk drive industry is architectural. The descriptions of innovation as incremental, radical, competence-enhancing, and competence-destroying are considered characteristics of innovation. Gatignon et al. (2002) distinguished the need to acquire new competence as a characteristic separate from the impact of innovation on existing competencies.

After constructing and validating measures for variables of complexity, locus, type and characteristics, Gatignon et al. (2002) constructed a linear regression to measure the impact of these variables on the time needed to market an innovation and the perceived marketing success of the innovation. Several of their findings confirm earlier research:

- Complex innovations take longer to market than simpler innovations.
- Innovations to core subsystems take less time to market if it builds on existing competencies.

Some of their findings are unexpected, however:

- Innovations to peripheral subsystems took longer to market than innovations to core subsystems.
- Architectural innovations took longer to market and were not associated with commercial success, which runs counter to many case studies provided in the disruptive literature.

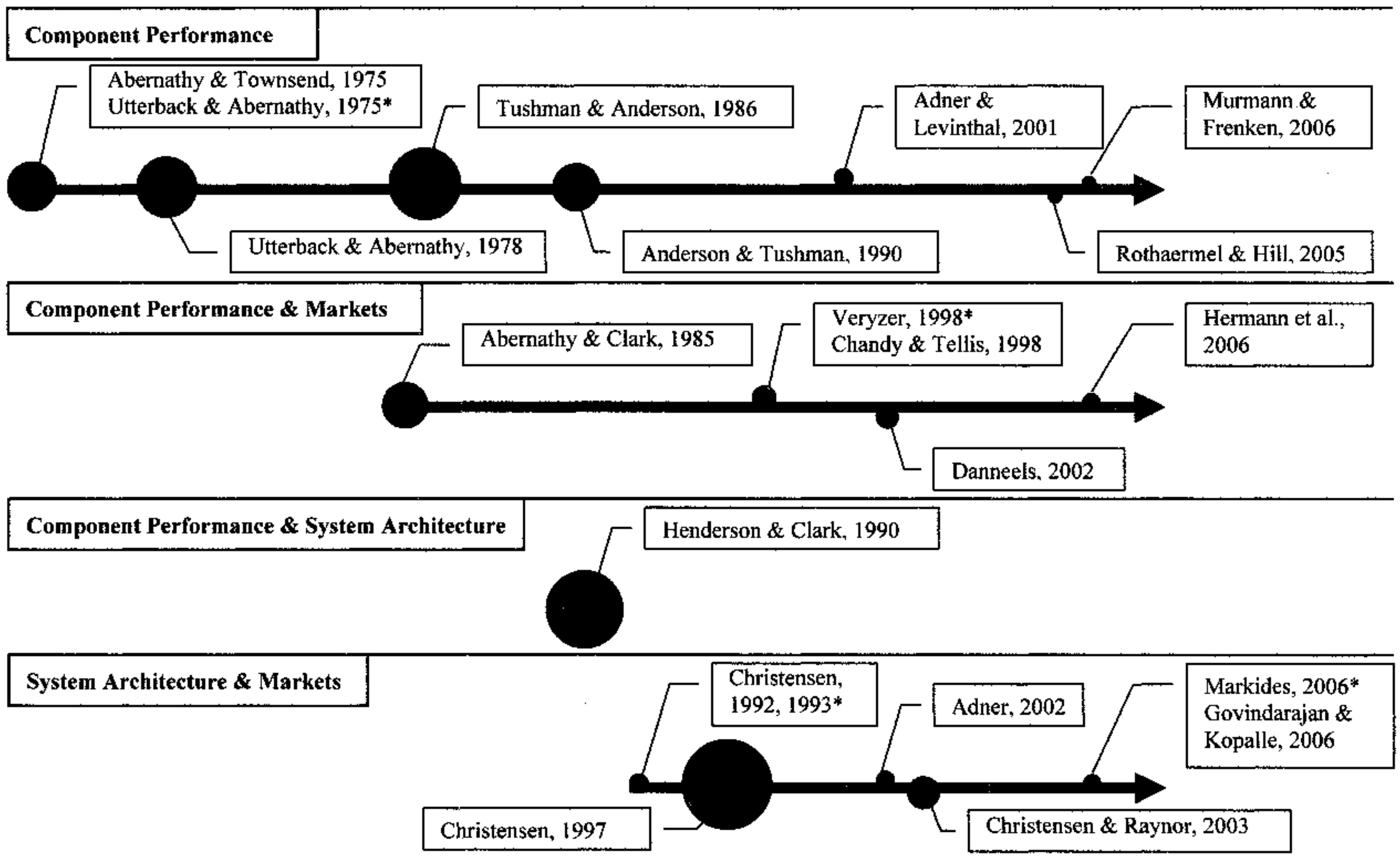
Sainio (2004) attempted to reconcile the theories of discontinuous and disruptive innovation with a typology of technological change and markets. From Sainio's (2004) perspective, both discontinuous innovations and disruptive innovations introduce new technologies. They transform existing markets and create new markets. However, this perspective blurs many distinctions between the theory of discontinuous innovation and the theory of disruptive innovation. Discontinuous innovations improve the performance of core technologies, while disruptive innovations introduce architectural innovations with existing technologies (often with worse performance in product attributes valued by mainstream markets). These distinctions are lost in Sainio's (2004) typology because the technological dimension does not account for multiple performance attributes and the possibility that some new products may actually have inferior performance when compared to existing technology. Finally, the core-architecture dimension introduced by Henderson & Clark (1990), which is a central argument in the theory of disruptive innovation, is not represented.

Even typologies seem to have dominant designs. Drawing on Google Scholar™, each of the typologies in Figure 19 was entered and the number of citations recorded was noted. The areas of the circles in Figure 19 roughly correspond to the number of Google Scholar™ citations. The data used in this figure is included in Appendix A. Granted, citation analysis is an inexact measure of article importance (Seglen, 1994). Just as dominant designs often do not contain the most advanced technology (Anderson et al., 1990) , the most cited articles might not be the best scientific argument. However, dominant designs are considered dominant because of their influence on follow on design. Similarly, the number of times an article is cited is likely to reflect its influence on subsequent research.

Figure 19 suggests that there have been five dominant typologies proposed between 1975 and today: the technology development cycle (Abernathy et al., 1978), the theory of discontinuous innovation (Tushman et al., 1986), the typology of transilience

(Abernathy et al., 1985); the introduction of architectural innovation (Henderson et al., 1990), and the theory of disruptive innovation (Christensen, 1997). There are three primary dimensions explored in these typologies: component performance, markets, and system architecture. Out of these typologies, two theories tend to dominate the literature of radical innovation at the industry level of abstraction – the theory of discontinuous innovation and the theory of disruptive innovation. The next chapter integrates these three dimensions into an integrated typology and positions the theories of discontinuous and disruptive innovation within it.

FIGURE 19
Evolution of the Theories of Contextual Technology[1]



[1] When two references are plotted on the same date, the circle represents the larger of the two and is annotated with an *. See Appendix A for details.

INTEGRATING THE THEORIES OF DISCONTINUOUS AND DISRUPTIVE INNOVATION

The science of classification is integral to the process of scientific research and theory development (Aldenderfer & Blashfield, 1984). The scientific method gathers knowledge by observing, forming and testing hypotheses through careful experimenting, analyzing and communicating (Shrake, Elfner, Hummon, Janson, & Free, 2006). Popper (1959: 276) described the scientific method as a "quasi-inductive" path. Inductive logic is used to form hypotheses and deductive logic to test these same hypotheses. Theories are created and form a hypothesis to explain observed patterns. Hypotheses are then tested through deductive logic. This sequence of "model → deduction → testing → induction → thinking → model" is also referred to as the "empirical cycle of critical rationalism" (Nijland, 2002: 214). The results of these tests enter the body of scientific knowledge as results are published – preferably in a manner that allows experiments to be replicated by others in the field.

It is problematic to say that theories are proven. No matter how thorough the deductive test, there is always some population that remains untested. Successive empirical tests may further substantiate a theory, but it is never proved. In fact, a theory that cannot be disproved is considered by many to be of no value (Grattan-Guinness, 2004). More commonly, the deductive test largely agrees with the hypothesis but some adjustment is needed. The results of tests are considered and inductively adapted to existing theory. A new hypothesis is created, and the cycle repeats.

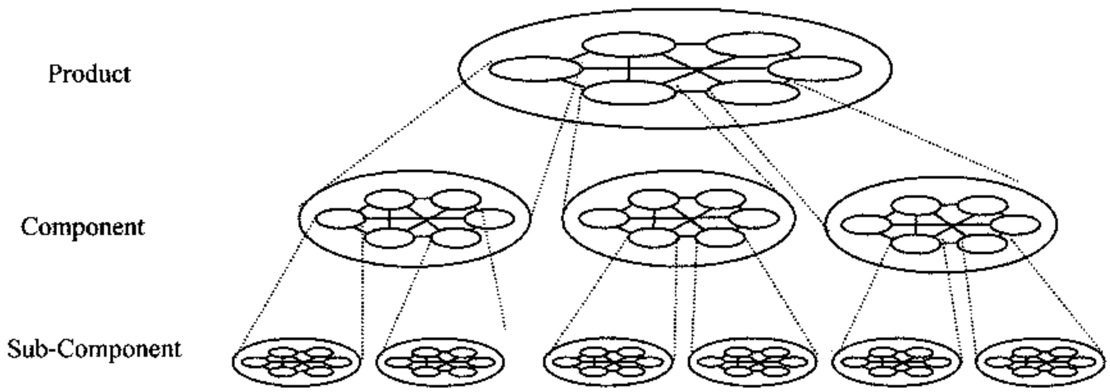
This research adopts McKelvey's (1982) rationale relating the science of classification to the inductive-deductive cycle of the scientific method. The inductive phase of the scientific cycle proposes to explain why something occurs. It relies upon logic and *a priori* rational thought. Typologies are *a priori* classifications that are built from theories. Therefore, typologies are representations of the inductive side of the inductive-deductive cycle. The deductive counterpart to the typology is the taxonomy. Taxonomies describe a sample of a selected population. If a comparison of the sample described by the taxonomy corresponds to the classification predicted by the typology, then the explanation underlying the typology is substantiated. This chapter established the *a priori* assumptions on which this typology is based.

A Framework for an Integrated Typology

This section creates a framework for an integrated typology based a priori assumptions drawn from the literature of contextual technology. The typologies of discontinuous and disruptive innovation are then deconstructed into their component variables and placed within the framework of the integrated typology. Each variable is examined to determine how it is measured and how it relates to the other variables. The new typology predicts the classification of radical innovations using the variables of both theories.

Hierarchical Systems. Products are best described as a hierarchy of systems where each level of the hierarchy is represented by subsystems and a design that links the subsystems together (Murmann et al., 2006; Tushman & Murmann, 1998). (See Figure 20) This system hierarchical view is present in Henderson & Clark's (1990) components and architectures, Christensen's (1992b) description of a hard disk drive as a nested architecture, Schilling's (2000) product modularity, and Murmann & Frenken's (2006) framework for research on dominant designs.

FIGURE 20
A Product as a Hierarchical System



The product is defined by individual components and the system architecture that result in a physical artifact with performance that is valued by customers at an established cost. Innovations within this hierarchical system will be measured as a change in performance or a change in cost at the product level of abstraction. Murmann & Frenken (2006) recommend that empirical research track the location where innovations take place. This typology will distinguish between innovations in components, innovations in the system architecture, and innovations to both.

The impacts of innovation differ as they are viewed throughout the hierarchy of the complex system within which it resides. For example, the rotary kiln transformed the U.S. cement industry between 1889 and 1895. The rotary kiln dramatically increased the barrels/day production output of American cement manufacturers while significantly reducing labor costs (Eckel, 1908). Anderson & Tushman (1990) classified the rotary kiln as a discontinuous improvement in the industrial capacity of cement manufacturers. However, customers buying cement were more likely to notice the increased availability and the reduced cost that the rotary kiln made possible. Therefore, products in this typology will follow the convention used by both Tushman & Anderson (1986) and Christensen (1997). The product characteristics of the innovation being classified will be measured from the perspective of the industry segment where the firm offering the product interacts with customers of the product. In the case of the cement industry, the innovative product is the rotary kiln. The attribute most valued by kiln customers was the barrel/day making capacity of the machine. The customers of concern are cement manufacturers and not the cement buying public.

Product Utility is a function of performance and cost. Adner & Levinthal (2001: 615) described a product's net utility threshold as the "highest price a consumer is willing to pay for a product that just meets his or her requirements." The idea that customer's demand more performance and reduced cost is integral to the economic value of innovation. Anderson & Tushman (1986, 1990) mapped product performance. Christensen's (1997) theory of disruption relies specifically on the concept of a utility threshold. Disruptions occur when customers whose performance demands have been over met are given a lower cost opportunity. This typology will distinguish between changes in performance and changes in cost.

Markets. The focus of this research is on how discontinuous and disruptive innovations cause the dominant designs in markets to change. The simplest models for market change assume that all markets develop dominant designs and the innovations either slowly adapt these designs (incremental innovation) or change them (discontinuous or disruption). Empirical research demonstrates that markets are more complex. First, dominant designs do not always emerge. Nair & Ahlstrom (2003) suggest that dominant designs may co-exist when the technology is complex and regulatory practices inhibit information sharing. Additionally, they note that the improvement of component performance may delay the choice of a dominant design as all competing designs benefit. This is further substantiated by Srinivasan, Lilien, & Rangaswamy's (2006) study where 33 of 63 products categories where dominant designs had not yet emerged. They provide evidence that suggests that the emergence of dominant designs might be delayed or stalled when the cost of sharing information is high (high appropriability), the utility of the product does not depend on other users (network effects), and when the innovation is more radical. However, the purpose of this research is to integrate the theories of discontinuous and disruptive innovation. Therefore, this typology will focus on the simple model of market change. Innovations either create a new market or change existing markets. The introduction of complexity into our understanding of market is beyond the scope of this research.

The theories of discontinuous and disruptive innovation can each be positioned within this typology. The theory of discontinuous innovation is a theory of component performance. It predicts the change in existing markets and new technologies increase product performance. The theory of disruptive innovation is a theory of system architectures and markets. It predicts change in existing markets as new architectures are developed from existing technologies and are introduced to customers whose demands have been exceeded by existing products (See Table 6).

Deconstructing Discontinuous Innovation

The term discontinuous can be as difficult to define as the term radical (Ehrnberg, 1995; Garcia et al., 2002). Discontinuities can be viewed across multiple industries,

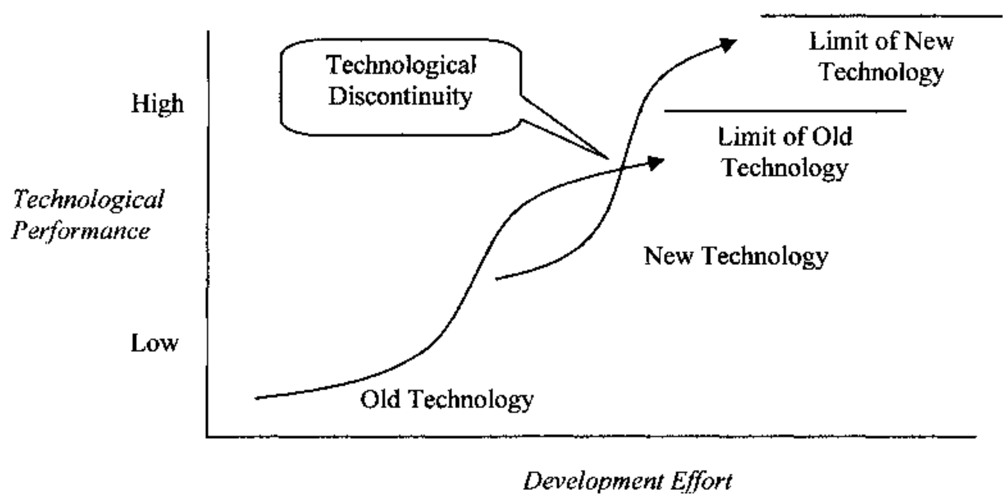
TABLE 6
Dimensions of an Integrated Typology

	Locus of Innovation		Product Utility		Markets	
Innovation Theory	Component	Architecture	Performance	Cost	Existing	New
Discontinuous	X		X		X	
Disruptive		X	X	X	X	X

within industries and within marketplaces (Garcia et al., 2002). While many researchers have measured discontinuities on a Likert scale based on questionnaires filled out by industry experts or senior managers (Garcia et al., 2002), this research focuses specifically on measures used by Tushman & Anderson's (1986, 1990) theory of discontinuous innovation.

In general terms, the theory of discontinuous innovation is wholly consistent with Foster's description of the S-curves of technology. "Technological change is a bit-by-bit, cumulative process until it is punctuated by a major advance" (Tushman et al., 1986: 441). Foster (1986) describes a technological discontinuity as the overtaking of one technology by another (overlapping S-curves). He describes technological advances as advancing on S-curves where performance is plotted against development effort. According to Foster (1986), the maturity of a technology is indicated when the technological return on investment (performance gain over effort) or slope of the S-curve shows diminishing returns. When a new technology's S-curve surpasses an existing technology, this causes a technological discontinuity. Foster (1986) noted that a major impediment for companies attempting to navigate a discontinuity is managing the transitions of skills from the old S-curve to the new (Figure 21).

FIGURE 21
Foster's S-Curves and Technological Discontinuity



The key variables that distinguish incremental innovations from discontinuous innovations are technological performance, technological design and time. Tushman & Anderson (1986) measured the technological performance of innovations in the cement, domestic airline and minicomputer industries. In each case, the parameters chosen to represent technological performance were identified *a posteriori* from the literature of the industry. In the cement industry, the barrel per day capacity of cement kilns was chosen. A year-by-year comparison was made of industry kiln capacity and the percentage improvement in kiln capacity was plotted over time. Seat-miles per year were similarly used to measure technological advance in the domestic airline industry and central processing unit time per cycle in the minicomputer industry. In each case, Anderson & Tushman (1990) used the most advanced technology on the market - the largest capacity kiln, the fastest minicomputer, or the largest seat-mile per year plane - to measure technological change.

Discontinuities were first described as "sharp price-performance improvements" (Tushman et al., 1986: 441). Price clearly contributes to why kiln capacity is important in the cement industry and why seat-miles/year is important in the domestic airline business. The advent of digital technology dramatically lowered the cost/per month of transmitting facsimiles (Baum, Korn, & Kotha, 1995). The work of Adner & Levinthal (2001) further emphasizes the significance of price in the innovation of products. Discontinuities might also result in significant changes in quality (Anderson et al., 1990). The introduction of radial tires significantly improved the safety of bias ply tires while also reducing the average cost/mile (Sull, Tedlow, & Rosenbloom, 1997).

However, in the literature cited above, price reductions, quality improvements and new dominant designs all resulted from a rapid advance in technological performance. The transition from analog to digital facsimile technology reduced the time necessary to transmit a page of data over phone lines from about 3 minutes to less than 1 minute (Baum et al., 1995). Improvements in the technological performance of facsimile transmission directly reduced operating costs since the time necessary to transmit a fax is directly related to the cost of the transmission over existing phone lines. Similarly, the improved life expectancy of a radial tire (40,000 miles versus 12,000 for a bias ply tire) directly translates into improved safety and reduced operating cost (Sull et al., 1997). Although not explicitly stated, there seems to be an underlying assumption within the theory of discontinuous innovation that an industry chooses its key measures of technological performance precisely because they will also deliver the price and quality improvements that industry customers demand. Table 7 provides a summary of measures of technological performance.

TABLE 7
Measures of Technical Performance in Discontinuous Literature

Reference	Description of Discontinuity	Industry	Measurement of Technical Performance
Tushman & Anderson, 1986	"…discontinuities offer sharp price-performance improvements over existing technologies" (441).	Cement	% Improvement in barrel/day production capacity of largest industry kilns.
		Airlines	% Improvement in seat/miles per year capacity of most capable plane flown.
		Minicomputer	Central Processor Unit speed.
Tushman & Anderson, 1990	"Product discontinuities are fundamentally different product forms that command a decisive cost, performance, or quality advantage over prior product forms" (607).	Cement and Minicomputers	Same as above.
		Glass Containers	% Improvement in capacity of fastest machine.
		Flat Glass	% Improvement of capacity of fastest machine.
Baum, Korn, & Kotha, 1995	"Technological discontinuities push forward limits of the previous technology making possible orders of magnitude or more improvements in organizational performance" (100).	Facsimile Technology	Minutes/page data transmission
Sull, Tedlow, & Rosenbloom, 1997	"Technological discontinuities often radically disrupt the pattern of commitments within an organization" (466-467).	Automobile Tires	Tire life expectancy in miles

TABLE 7
Measures of Technical Performance in Discontinuous Literature (Cont'd)

Reference	Description of Discontinuity	Industry	Measurement of Technical Performance
Rice, O'Connor, Peters, & Morone, 1998	"…breakthrough innovations…a 'game changer' " (52)	Various	(1) 5-10 times improvement in performance, or (2) 30-50% reduction in cost, or (3) New-to-the-world performance features
Norling & Statz, 1998	"…the sudden appearance of a major breakthrough in technology that can yield entirely new products, processes, or services." (41)	Chemical Resin	Improved toughness and clarity of resin
Veryzer, 1998	"Discontinuous innovation refers to radically new products that involve dramatic leaps in terms of customer familiarity and use." (305)	Various	Improvement in Technology, and/or Improvement in Customer Performance
DeTienne & Koberg, 2002	"…major changes or innovations in basic products or services or programs offered or markets served, or the creation of new major product/service programs leading to new or expansion of current markets." (353).	Aerospace Electronic components and superconductors Telecommunications	Self-report based upon definition. (Questionnaire)
Rothaermel & Hill, 2005	Same as Tushman & Anderson, 1986	Computer Steel Pharmaceutical Telecommunications	Price-Performance Improvement

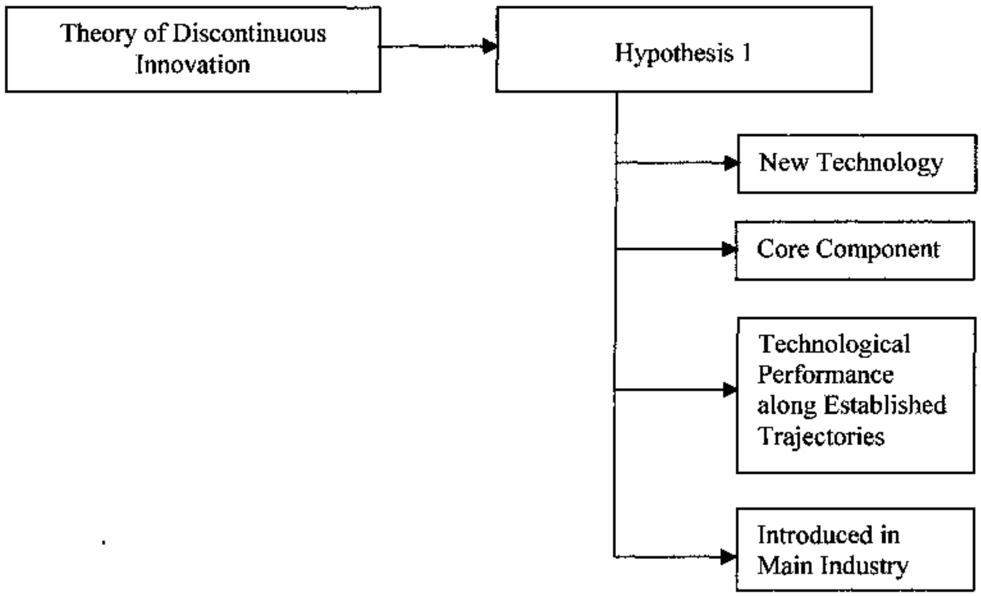
Ehrenberg (1995: 445) asks, "How much change must there be for there to be a technological discontinuity?" There is no consensus on an answer. Tushman & Anderson (1986, 1990) noted peaks in technological performance. Others noted significant changes or step jumps in performance (Saul et al, 1997; Baum et al., 1995). Perhaps this is why discontinuities are difficult to identify *a priori.* What is clear is that technological discontinuities result in new dominant designs (Anderson et al., 1990).

Typically S-curves plot technological performance against development effort (Foster, 1986) or time (Christensen, 1992a). During the high growth periods of the S-curve, significant growth might be observed and might confuse discontinuities with incremental innovation. Anderson & Tushman (1990: 607) distinguished between rapidly developing incremental innovation and discontinuous innovation by specifying that discontinuous innovations are also characterized by a new technological design:

> Product discontinuities are fundamentally different product forms that command a decisive cost, performance, or quality advantage over prior product forms.

Each of Anderson & Tushman's (1990) product discontinuities is characterized by changes in the technology of core components. Jet engines replace piston engines. Diesel engines replace steam engines. As shown in Chapter Two, the locus of the technological change for discontinuous product innovation is expected to be in the product's core components rather than in its architecture as defined by Henderson & Clark (1990). The interdependent variables that describe discontinuous innovation are shown in Figure 22. Stated in their null form, the first set of hypotheses of this research are:

FIGURE 22
Defining Variables of Discontinuous Innovation



Hypothesis 1. *There is no natural grouping of discontinuous innovations where a new technology is introduced into a products core and results in a new dominant design that significantly outperforms previous designs along established performance parameters while competing in the main market of an industry.*

Hypothesis 1a. *If a natural grouping of discontinuous innovations is present, the introduction of new technology is not a necessary component.*

Hypothesis 1b. *If a natural grouping of discontinuous innovations is present, the introduction of a new core component is not a necessary component.*

Hypothesis 1c. *If a natural grouping of discontinuous innovations is present, the improvement of performance along established trajectories is not a necessary component.*

Hypothesis 1d. *If a natural grouping of discontinuous innovations is present, the introduction of the new dominant design within the main market of the industry is not a necessary component.*

Deconstructing Disruptive Innovation

Researchers describe many types of innovation as disruptive. Denning (2007: 22) describes the theory of disruption as a sort of a Kuhnian paradigm shift, where "Disruptive innovations shift to new paradigms (new belief systems and practices); because they change who has power, they are likely to be resisted and not win immediate social acceptance." Others have tried to expand the original concept to include "top-down" innovations (Carr, 2005; Rao, Angelov, & Nov, 2006), technological fusion (Hacklin, Raurich, & Marxt, 2004), or business model innovation (Markides, 2006).

Christensen (2006: 42) laments his use of the word *disruptive*:

> The term *disruptive* has many prior connotations in the English language, such as "failure" and "radical," in addition to the phenomenon to which I applied it. I fear this is why we see so much post hoc definition by the uninformed. As noted following, Grove (1998) proposed that the phenomenon should be labeled the "Christensen Effect" to eliminate this misunderstanding. Possibly we should have taken his advice.

This research relies upon Christensen's definition of the theory to identify the variables used to classify disruptive innovations.

As described earlier, low-end disruptions occur when technological performance exceeds market needs. At this point, architectural innovations that offer new value in the market take hold and replace existing dominant designs. Therefore, the variables of

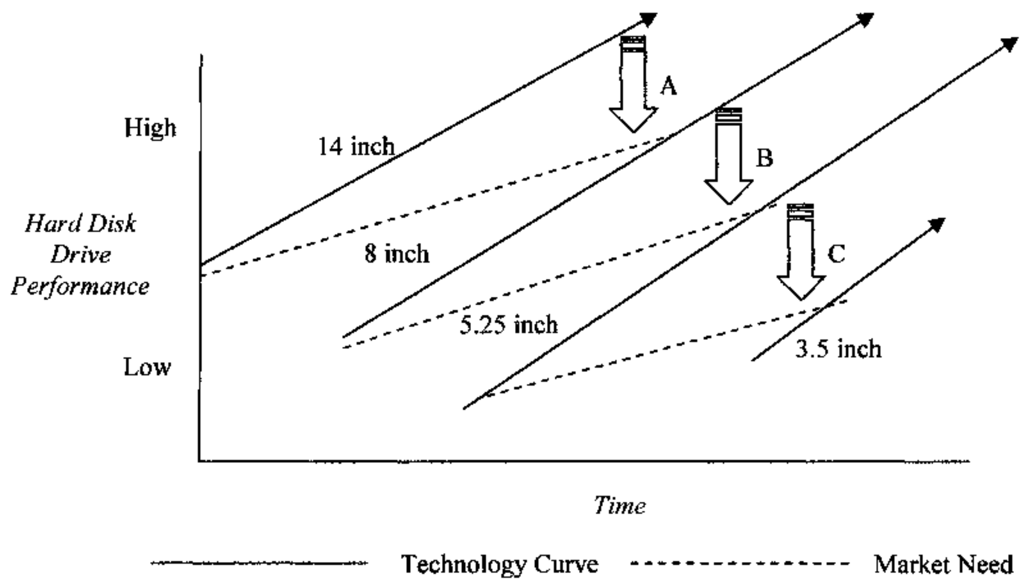
TABLE 8
Measures of Technical Performance in Low-end Disruption

Reference	Technological Disruption	Performance Measure
Christensen 1992a	14 inch – 8 inch Hard Disk Drive 8 inch – 5.25 inch Hard Disk Drive 5.25 – 3.5 inch Hard Disk Drive	Hard Disk Capacity in Mbytes
Christensen 1997	Cable driven – Hydraulic Excavator	Bucket Capacity in Cubic Yards
	Integrated Steel Mills – Minimills	Quality of the Output Steel
	Laser Jet – Ink Jet Printer	Printer Speed in Pages per Minute

technological performance, market need, system design, and market value must be defined in order to classify low-end disruptive product innovations.

Christensen identifies key technological parameters in a manner similar to the research of discontinuous innovation (Table 8). His initial research measured the technological performance of hard disk drives using disk capacity in Mbytes (Christensen, 1992b). For example, Christensen (1992a) notes that in 1980, the 14 inch hard disk drives dominate the minicomputer market with a capacity of nearly 400 Mbytes when low-end 8 inch drives could only achieve 40 Mbytes. By 1984, 94% of minicomputers were using 8 inch drives or smaller with a disk drive capacity of roughly 300 Mbytes. When the disruption from 14 inch drives to 8 inch drives occurred, the technological performance of the dominant design lowered. Christensen's *The Innovator's Dilemma* shows a repeating pattern of

FIGURE 23
Technological Performance during a Low-End Disruption
(Adapted from Christensen 1997)



A – Substitution of 14 inch drives for 8 inch drives in mainframe computers

B – Substitution of 8 inch drives for 5.25 inch drives in minicomputers

C – Substitution of 5.25 inch drives for 3.5 inch drives in desktop computers

low-end disruptions as low-end designs replace existing higher market dominant designs (Christensen, 1997). After the disruption, the technical performance of the new design continues to improve, often at the same pace that it previously improved (See Figure 23).

In order to understand this phenomenon, one must distinguish between the average technological performance of the chosen parameter and what Christensen describes as the technological performance demanded by market need. The technological performance shown in Figure 23 as a solid line, is calculated from the average value of the parameter being measured (Christensen & Rosenbloom, 1995). These curves are typically drawn on log-linear graphs as straight lines and as such represent an average exponential growth rate. Market need (the dotted lines in Figure 23) is calculated by rank ordering the products offered in a given year and measuring the technological parameter of the median priced product (Christensen et al., 1995: 257):

> Because drives with higher capacities were available in the market than the capacities offered with the median-priced systems, we state …that the…trajectories …represent the capacities 'demanded' in each market. In other words, the capacity per machine was not constrained by technological availability. Rather, it represents a choice for hard disk capacity, made by computer users, given the prevailing costs.

A recurring observation in the disruptive literature is that the technology curve of an industry typically grows more rapidly than market demand (Christensen et al., 2004: 278-279):

> However, firms almost always improve their products faster than customers can change to use the new innovations. Therefore, incumbent firms tend to create new products and services at a pace …that outstrips the ability of customers in various levels or tiers of the market to use the improvements.

According to Christensen, it is this growing gap between the technological capacity of the product and the market need that creates the opportunity for disruption.

Adner (2002) explained that disruption is one of three potential results when two markets – in this case a low-end and a high-end market - compete. If the low-end product holds no appeal to the high-end market and vice versa, then the markets remain in competitive isolation. When the low-end product and the high-end product both appeal to each other's markets, a competitive symmetry develops. Low-end disruption results when the low-end product appeals to the high-end market but the high-end product holds no appeal to the low-end market. Adner (2002) called this competitive asymmetry and suggests that this is an underlying feature of disruptive innovation. Adner (2002) also proposed that Christensen's focus on dollar/megabyte may be wrong. Instead, Adner

(2002) suggested that absolute price may be the more important factor. "Customers with sufficiently satisfied functional requirements are more concerned with differences in absolute price than with differences in price/performance points" (Adner, 2002: 684). He noted that while 3.5 inch disk drives have disrupted 5.25 inch disk drives, laptops have not disrupted desktop computers even though they offer functional parity in all areas except price.

> The current analysis suggests that the essential aspect of consumer choice which allows for disruptive displacement may be consumers' decreasing marginal utility from performance improvements beyond their requirements, rather than a new found appreciation for previously marginal attributes. (Adner, 2002: 684-685)

Adner & Zemsky (2003) explored the relationship between technology capacity and market demand. They demonstrated that while the gap between technology capacity and market demand – a gap they called 'performance over supply'- assists in disruption, it is not necessarily required. Instead, Adner & Zemsky (2003) showed the disruptive influence of the lower margin costs of low-end technologies. Using economic models, they illustrate how new technology firms who have achieved low margin costs have incentives to pursue high volume strategies. Combined with advancing technological capacity, the lower margin products have great disruptive potential because they can offer the capacity demanded by the market at reduced cost.

The theory of disruptive innovation has evolved from its early focus on technology to its current focus on business models (Christensen, 2006). The technological dimension remains a prerequisite condition for disruption. The performance over supply that Christensen (1997) observed and the competitive asymmetry that leads to disruption that Adner & Zemsky (2003) theorized both require

FIGURE 24
Henderson & Clark (1990) Typology of Component versus System Innovation

	Core Technology Reinforced	Core Technology Overturned
Unchanged Relationship Between Components	Incremental Innovation	Modular Innovation
New Relationship Between Components	Architectural Innovation	Radical Innovation

the improvement of technological performance in core components, but disruption is " a business model problem, not a technology problem" (Christensen, 2006: 48). Disruption results when the business models of two markets develop products that compete asymmetrically.

The innovative change that is observed in a disruption is a change in value or cost. Christensen (1997) originally proposed that new attributes such as size, reliability, or cost might become the basis of competition after a disruption. Adner (2002) suggested that cost alone might be sufficient.

The theory of disruptive innovation initially measured system design changes according to the typology of Henderson & Clark (1990) (Christensen, 1997) (See Figure 24). Christensen (1997) first described disruptive innovations as originating from architectural innovation. New entrants in niche markets create new product designs by putting existing core technologies together in new architectures. The margin costs of these new designs are much better than in high end products but the initial performance of the new product is insufficient to compete asymmetrically for the higher markets. When the disruption occurs, the new market dominant design does not represent a leap forward in technological capability. Instead, it represents a new architecture with improved values (new attributes or reduced cost) for high-end market customers.

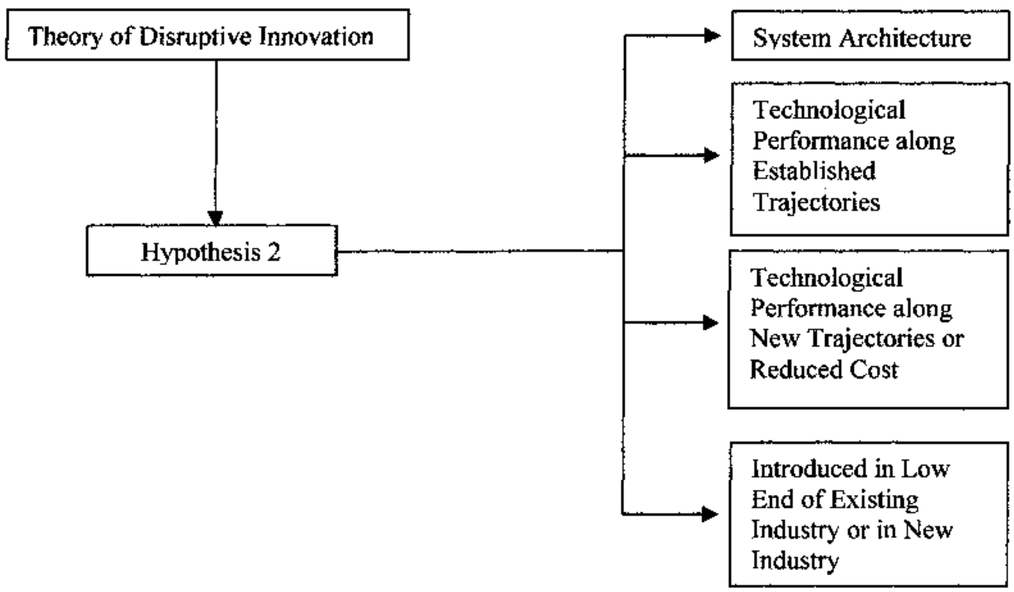
More recently, Christensen (2006: 49) has rescinded his emphasis on a technological foundation to disruptive innovation:

> I decided that labeling the phenomenon as disruptive technology was inaccurate. The technology did not make the incumbent response difficult. The disruptive innovation in business models made it vexing, and I have subsequently sought to sue the term disruptive innovation.

As a result, Christensen & Raynor's (2003) list of disruptive innovations sometimes use new technologies (inkjet printers), old technologies (minimills), and changes in core technologies (Seiko watches) and existing core technologies (Southwest Airlines). In the end, the technologies new and old are recombined in a new architecture with a new business model that competes asymmetrically with the dominant industry model.

So far, disruptive innovation has been discussed primarily from the perspective of low-end disruption. In *The Innovator's Solution: Creating and Sustaining Successful Growth*, Christensen & Raynor (2003a) introduced the concept of new market disruption to the theory of disruptive innovation. In new market disruptions, new products are offered to new customers rather than the low-end market customers we have previously been discussing. Christensen & Raynor (2003) described the first personal computers and the first battery powered pocket radios as new market products. As the new markets develop, they enjoy advantages over low-end markets in that they can establish lower

FIGURE 25
Defining Variables of Disruptive Innovation



margin costs and new product attributes without competing against established markets. Eventually, the improvements of core technologies allow these new market products to compete asymmetrically with established markets and pull customers from existing markets into the new market creating a "new market" disruption.

While the development of the new market differs from the development of low-end markets, the variables of technological performance, market need, system design, and market value are sufficient to describe the disruption since the core mechanism underlying both low-end and new market disruptions is asymmetric competition. The variable of source market is included to describe whether the disruption originated in a low-end market or in a new market (See Figure 25). Stated in their null form, the second set of hypotheses in this research are:

Hypothesis 2. *There is no natural grouping of disruptive innovations where a new architecture is introduced that results in a new dominant design that equals or underperforms existing designs along established parameters while shifting competition to new performance parameters (such as size or reliability) or reduced cost while competing in the low end or from an adjacent market of an industry.*

Hypothesis 2a. *If a natural grouping of disruptive innovations is present, the introduction of a new architecture is not a necessary component.*

Hypothesis 2b. *If a natural grouping of disruptive innovations is present, the presence of a dominant design that equals or underperforms existing designs along established parameters is not a necessary condition.*

Hypothesis 2c. *If a natural grouping of disruptive innovations is present, the improvement of performance along new parameters or the reduction in cost is not a necessary component.*

Hypothesis 2d. *If a natural grouping of disruptive innovation is present, the introduction of the new dominant design in the low end of existing markets or within adjacent markets is not a necessary component.*

Completing the Integrated Typology

Table 9 identifies the seven variables that are required to define the theories of discontinuous and disruptive innovation. There is no simple 2 or 3 dimensional construct that will fully distinguish discontinuous innovations from disruptive. The literature of contextual technology tends to partition discontinuous and disruptive innovations as distinct and separate phenomena. Therefore, this integrated typology establishes the

TABLE 9
Integrated Typology for Classifying Shifts in Dominant Design

Dimensions of Typology		Interdependent Variables	Discontinuous Innovation	Disruptive Innovation
Locus of Innovation	Component	New Technology Introduced	Yes	
	Component	Core Component Change	Yes	
	System Architecture	System Architecture Change		Yes
Product Utility	Performance	Product Performance along Establish Parameters	Better	Same or Worse
	Performance	Customer Shift in Established Parameters		Yes
	Cost	Reduced Cost		Yes
Market	Existing	Where was the New Product Introduced?	Main Industry	Low-end or New Market

criteria upon which to classify product innovations as either discontinuous or disruptive based upon these seven variables. This serves several purposes. First, it establishes a starting point for a typology that is firmly grounded in the literature of innovation. Second, it provides the hypothesis required to evaluate the usefulness and generalizability of these theories in describing a sample of innovations. Third, this typology enables this research to distinguish between shifts in dominant design that are predicted by the typology and anomalies that require further investigation.

The appearance of dominant designs is a signal event identifying innovations with the potential to be either discontinuous or disruptive. As described earlier, Anderson & Tushman (1990) explained that a new dominant design ends the era ferment initiated by the discontinuous innovation (See Figure 7).

> A dominant design is the second watershed event in a technology cycle, marking the end of the era of ferment. A dominant design is a single

> architecture that established dominance in a product class (Abernathy, 1978; Sahal, 1981). Once a dominant design emerges, future technological progress consists of incremental improvements elaborating the standard and the technological regime becomes more orderly as one design becomes its standard expression. (Anderson et al., 1990: 613)

Christensen & Bower (1996) cited the shift in the dominant designs of hard disk drives as they described the waves of disruptive innovation that occurred in the mainframe and minicomputer industries.

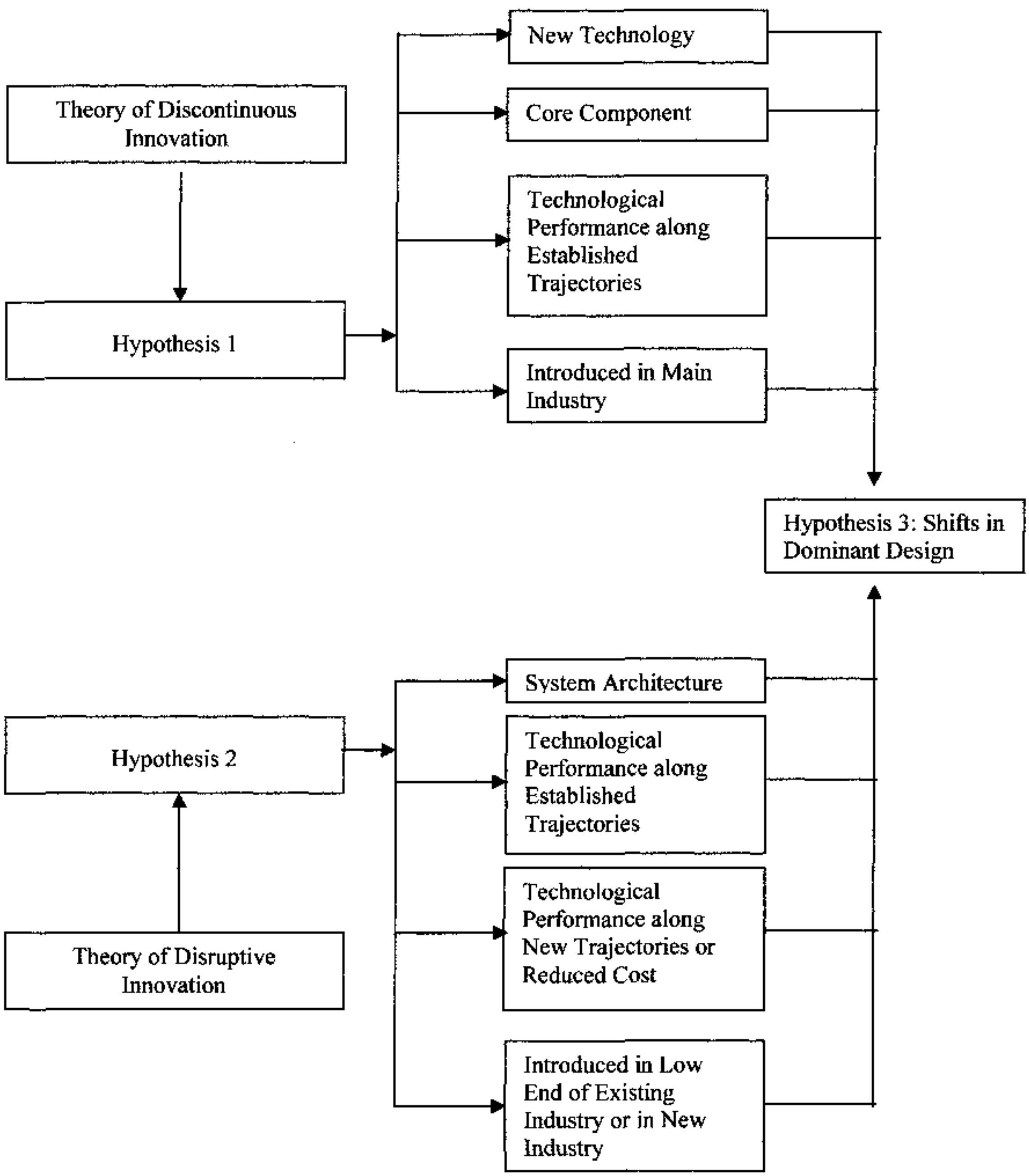
> Hence, all but one of the makers of 14-inch drives were driven from the mainframe computer market by entrants firms that got their start making 8-inch drives for minicomputers. The 8-inch drive makers, in turn, were driven form the minicomputer market, and eventually the mainframe market, by firms which led in producing 5.25-inch drives for desktop computers. (Christensen et al., 1996: 205-206)

This research uses shifts in dominant design as the *taxa* or object of classification in our research.

A sample of dominant design shifts from various industries classify into three groups using this method. First, those shifts that result from discontinuous innovations. Second, shifts in dominant designs that result from disruptive innovation. Third, any shifts in dominant designs that are not well described by either theory. Combining the variables identified in our earlier deconstruction of the theories, the variables can now recombined into an integrated typology in Figure 26 and Table 9 that will predict the grouping of classification of discontinuous and disruptive innovations according to Hypotheses 1 and 2. Stated in its null form, the third hypothesis of this research is:

Hypothesis 3. *A taxonomy constructed from shifts observed in the dominant design of an established industry does not display natural clusters of innovation as predicted by the typology (Table 9) constructed from the theories of discontinuous innovation and disruptive innovation.*

FIGURE 26
Integrated Theories of Discontinuous and Disruptive Innovation



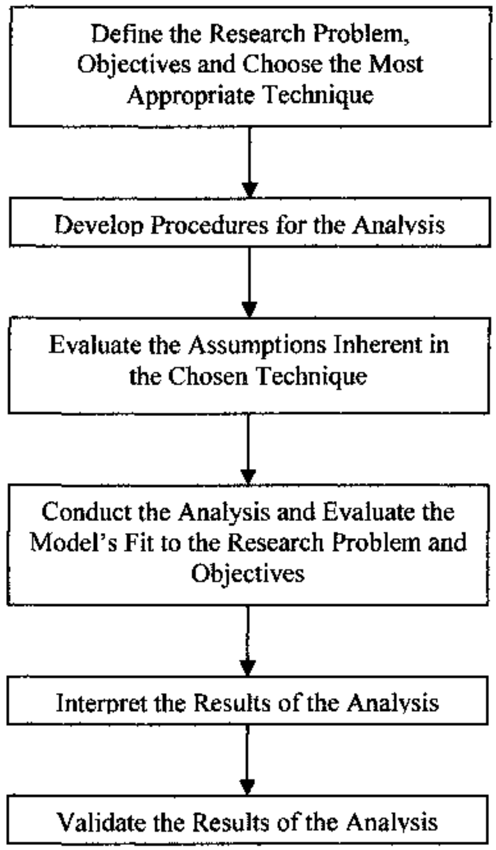
RESEARCH METHODOLOGY

Research Design for Multivariate Analysis

The purpose of this chapter is to describe the methodology this research employs to test the hypotheses developed in the previous section. The goal is to collect data on a sample of innovations across many industries and test to see how well the data can be structured using the theories of discontinuous and disruptive innovation. This research does not attempt to predict the occurrence of a shift in the dominant design, or to establish the dependence of a dominant design shift on variables such as system design or product performance. Additionally, this research distinguishes between the technological, market, and industry factors that combine to cause a shift in a dominant design from the ability of firms within the industry to survive the shift. Multivariate techniques that explore the interdependent nature of our variables are best suited to answer our research questions when variables are not being defined as dependent or independent (Hair, Black, Babin, Anderson, & Tatham, 2006). The structured approach to multivariate analysis as proposed by Hair et al. (2006) is used as shown in Figure 27.

The Research Problem. The problem proposed in this research is to test the usefulness of an integrated typology constructed from the theories of discontinuous and disruptive innovation. Each of these theories was developed independently and has evolved over time to be among the most important theories used to describe the evolution of technological innovation in industries from a contextual technology perspective. An integrated typology is proposed that predicts how the variables identified can be used to

FIGURE 27
Approach to Multivariate Data Analysis (Adapted from Hair et al., 2006)



classify shifts in dominant designs according to the theories of discontinuous and disruptive innovation (See Table 9 from the previous section).

The Research Objective. The objective of this methodology is to design a test to determine how well the theories of discontinuous and disruptive innovation describe the shifts of dominant designs observed at the industry level (Hypothesis 1 and 2) and to test how well a single typology can be used to integrate the theories into a single classification structure (Hypothesis 3). Cluster analysis is well suited to meet both of these objectives. If the theories could be described with only two or three variables, then simple descriptive analysis might suffice to test for structure in the data. However, the literature review conducted earlier shows many two-dimensional typologies of innovation that have been constructed over the years and none capture the full multi-dimensional complexity of innovation. "It is difficult for humans to obtain an intuitive interpretation of data embedded in a high-dimensional space" (Jain, Murty, & Flynn, 1999: 268).

Cluster Analysis. Cluster analysis does not produce a result that is true or false. Instead, it provides a structuring of the data that is more or less useful (Everitt, Landau, & Leese, 2001). The theories of discontinuous and disruptive innovation predict that clusters should exist (Hypothesis 1 and 2). They describe the grouping of variables that should be most effective in identifying the common features of each type of innovation (contributing to homogeneity within each predicted cluster) and that should distinguish between each type of innovation (contributing to heterogeneity between groups). The predicted presence of clusters is an important precondition to cluster analysis. "We want to cluster only if clusters exist…the ability of procedures to find non-existent clusters is established" (Cormack, 1971: 345-346).

It is important to re-emphasize that cluster analysis is inherently subjective (Jain et al., 1999: 290).

> As a task, clustering is subjective in nature. The same data set may need to be partitioned differently for different purposes. For example, consider a *whale*, an *elephant*, and a *tuna fish* [Watanabe 1985]. Whales and elephants form a cluster of *mammals*. However, if the user is interested in partitioning them based on the concept of *living inwater*, then whale and tuna fish are clustered together. Typically, this subjectivity is incorporated into the clustering criterion by incorporating domain knowledge in one or more phases of clustering.

It is the underlying theory and the purpose of our research that makes cluster analysis appropriate. This research does not test if the theories of discontinuous or disruptive innovation are true or false. In essence, this research tests the usefulness of the theories of discontinuous and disruptive innovation in classifying the shifts of dominant designs as observed in industry.

The use of cluster analysis to test hypothesis is well established (Aldenderfer et al., 1984; Hair et al., 2006; McKelvey, 1982).

> …although viewed principally as an exploratory technique, cluster analysis can be used for confirmatory purposes. In such cases, a proposed typology (theoretically based classification) can be compared to that derived from the cluster analysis" (Hair et al., 2006: 569)

In using cluster analysis to test a proposed typology, it is important that the form of the clusters can be deduced from the typology that is being tested (Romesburg, 1984). This is why Hypothesis 3 is expressed in the form of Table 9. This is the hypothesized grouping of variables deduced from the theories of discontinuous and disruptive innovation that is expected to produce clusters in our analysis.

Techniques of discriminant analysis, factor analysis, principal component analysis, multidimensional scaling, and structural equation modeling were also considered for this analysis before choosing cluster analysis as the most appropriate technique. Discriminant analysis uses *a priori* theory to construct clusters.

> It is important to understand the difference between clustering (unsupervised classification) and discriminant analysis (supervised classification). In supervised classification, we are provided with a collection of *labeled* (preclassified) patterns; the problem is to label a newly encountered, yet unlabeled, pattern. Typically, the given labeled (*training*) patterns are used to learn the descriptions of classes which in turn are used to label a new pattern. In the case of clustering, the problem is to group a given collection of unlabeled patterns into meaningful clusters. In a sense, labels are associated with clusters also, but these category labels are *data driven*; that is, they are obtained solely from the data. (Jain et al., 1999: 265)

Discriminant analysis is useful once the groups are defined and it is necessary to classify a new object to either one group or the other (Everitt et al., 2001). For example, if it was well established which innovations were discontinuous and which were disruptive, then discriminant analysis could be used to develop coefficients for each of the variables here and compare them to theory. However, a central research question of this research is whether discontinuous and disruptive innovation are truly distinct phenomenon (H3); therefore, discriminant analysis was rejected (as was logistic regression – regression with a binary dependent variable).

Factor analysis and principal components analysis are particularly useful in analyzing the role of variables in describing a multivariate array of data. The objective of these techniques is to reduce the dimensionality of the data while retaining the maximum amount of information in the data set (Hair et al., 2006). These techniques are often used in conjunction with cluster analysis to manipulate the variables used to construct the cluster analysis (Aldenderfer et al., 1984; Everitt et al., 2001; Hair et al., 2006). Others caution that use of these techniques in cluster analysis without first understanding the underlying cluster structure and the effect that these dimensionality changes might cause should be avoided (Kettenring, 2006). Factor analysis was rejected because it might reduce the dimensionality of the variables in Table 9 in such a way that they cannot be directly mapped back to the theories of discontinuous and disruptive innovation. It is important for us to see how the variables described by theory interact in order to draw conclusions required to test our hypotheses. Multidimensional scaling was also rejected because (1) it is typically used in the mapping of people's perceptions to object (not considered useful in the testing of our hypotheses) and (2) its manipulation of the variables into "perceptions" would hide the inherent relationship between the variables of the theories of innovation and the results of the analysis.

Finally, structured equation modeling is a plausible approach but would require modeling dependent relationships between the variables of discontinuous and disruptive innovation in order to support a confirmatory factor analysis (Hair et al., 2006). The intent of this research is not to test the ability if the theories of innovation to *predict* shifts in dominant designs (dependence) but instead to test their ability to *classify* or *describe* innovations. From this perspective, cluster analysis is viewed as a simpler approach that does not depend on dependence between specific variables. This research examines the interactions between all of the variables (interdependence) in order to test our research hypotheses.

Cluster analysis has frequently been used to analyze the classification of innovative firms. De Jong & Marsili (2006), Peneder (2002), and Evangelista (2000) used cluster analysis to identify clusters of innovative firm types (capital driven, S&T based, Supplier-dominated, etc). The "industry cluster" was a central theme of Porter's *The Competitive Advantage of Nations* (1990) and has spurred the use of cluster analysis to identify regions of economic activity (Jacobs & Jong, 1992). Lawless & Anderson (1996) used cluster analysis to identify niches in markets in their study of generational innovation.

Adams (2003) used cluster analysis to explore a generalized classification of innovation. He employed a three-step methodology to explore innovation in the United Kingdom's National Health Service. First, he inductively generated a set of variables from literature reviews and semi-structured interviews. The results of this research were

TABLE 10
Innovation Types from Adams (2003) Cluster Analysis

Variable	Variable Description	Innovation Type I	Innovation Type II	Innovation Type III
Disruption	Changes existing practices in a disruptive manner	Low	High	
Risk	Threatens individuals or the organization; inherently risky	Low	High	
Adaptability	Ability to modify the innovation	High		
Actual Operation	Satisfaction of original need	High		Low
Observability	Visibility of innovation to others	High		Low
Scope	Extent of change required by the innovation		High	Low
Complexity	Extent of change required in interdependent systems		High	
Uncertainty	Lack of knowledge, concern over feasibility			Low
Relative Advantage	Extent of improvement created by innovation			Low
Profile	Extent that individual, group or organizational visibility is raised			Low

coded using content analysis to develop the attributes to be used for classification. Second, Adams (2003) conducted a cluster analysis and validated the existence of three clusters of attributes (shown in Table 10). He concluded his research by conducting further semi-structured interviews to explore the meanings of the clusters identified in his cluster analysis.

Adams (2003) approached the topic more from the perspective of a sociologist than a technologist (Gopalakrishnan et al., 1997). His research does not include any reference to the theories of discontinuous or disruptive innovation. As a result, while his research provides us an example of how cluster analysis might be used to develop a classification of innovation, it provides little assistance in aiding our test of how best to integrate the theories of discontinuous and disruptive innovation.

Procedures for Cluster Analysis

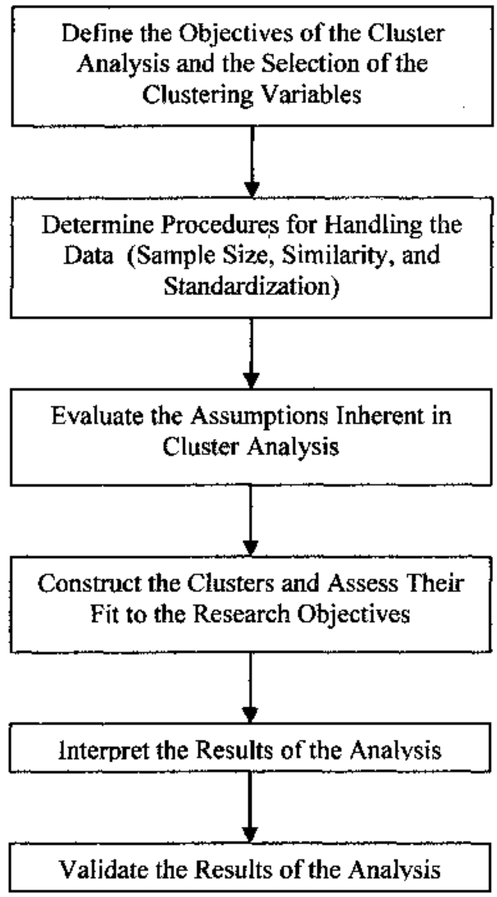
The procedures for conducting cluster analysis are broken into three broad phases (1) examination of the data field; (2) selection of the methods or algorithms for clustering; and (3) assessment of the results (Kettenring, 2006). The procedures outlined in Hair et al. (2006) (See Figure 28) form the basis for cluster analysis in this research.

Clustering Objective. The objective of the clustering analysis is to construct a taxonomy that can be compared to descriptions of theory (Hypothesis 1 and 2) and the proposed typology (Hypothesis 3) in order to test the usefulness of the theories of discontinuous and disruptive innovation in the description of shifts in dominant designs within industries.

Clustering Variables. The selection of the clustering variables has a significant impact on the subsequent formation of clusters.

> Any application of cluster analysis must have some rationale upon which variables are selected. Whether the rationale is based upon an explicit theory, past research, or supposition, the researcher must realize the importance of including only those variables that (1) characterize the objects being clustered, and (2) relate specifically to the objectives of the cluster analysis. (Hair et al., 2006: 569-570)

FIGURE 28
Procedures for Cluster Analysis (Adapted from Hair et al., 2006)



The purpose of this analysis is to test a specific set of hypotheses that are linked with established theories of innovation. It is not intended as an inductive exploration of data structure. As a result, the variables of this analysis must be directly related to the variables identified in our hypothesis (Romesburg, 1984). "Ideally, variables should be chosen within the context of an explicitly stated theory that is used to support the classification" (Aldenderfer et al., 1984: 20). The variables of this research were deduced from the theories of discontinuous and disruptive innovations outlined in Chapters 2 and 3 and are shown in Figure 26.

As the cluster analysis is conducted, the variables are examined to determine their role in the formation of clusters:

> The researcher is always encouraged to examine the results and to eliminate the variables that are not distinctive (i.e., that do not differ significantly) across the derived clusters. This procedure enables the cluster techniques to maximally define clusters based only on those variables exhibiting differences across the objects. (Hair et al., 2006: 570)

In this analysis, each of the variables will be examined for their contribution to the formation of clusters. Variables "that do not differ significantly across clusters" will be considered for removal and discussed in the cluster analysis results.

Some cluster analysis begins with a primary component analysis in order to project the multiple dimensions of the data into a smaller number of dimensions to make the results more informative (Everitt et al., 2001). Others caution that the ability of researchers to cull information from complex data sets may be confounded by reducing the data's dimensionality except in special circumstances (Kettenring, 2006). Since our theory and resulting hypothesis provide us with the variables of our analysis, there is no desire to reduce the dimensionality of this data with techniques such a primary component analysis or factor analysis.

- **New Technology (P_1= 0 (Existing) or 1 (New)).** Does the shift in dominant design introduce a new technology to the industry or does it use existing technology in the industry in a new way? The variable is specifically worded to examine technology from the perspective of the industry. For example, the construction of cylinders was not a new technology in general but was first applied to the process of manufacturing cement in the construction of a rotary kiln in about 1892. Tushman & Anderson (1986) considered this a new technology.

Alternatively, the use of electric arc furnaces in the metals industry spans decades but the evolution of the use of the electric arc furnace in minimills used an existing technology in a new and disruptive business model. Christensen (1997) would consider this the use of an existing technology. This is a binary variable with values of 0 for existing technologies and 1 for new technologies.

- **Core Component Design (P_2= 0 (Existing) or 1 (New)).** Does the shift in dominant design represent a change to the core components of the product design? Henderson & Clark (1990) distinguished between changes to core component and changes to system architectures. This variable measures changes in core component design as change in dominant designs are observed in order to test Hypothesis 1. This is a binary variable with a value of 0 if no changes are detected in core technologies and 1 for changes observed in core technologies.
- **System Architecture Design (P_3= 0 (Existing) or 1 (New)).** Does the shift in dominant design introduce a change to the system architecture of the product design? Christensen associated changes to system architectures with disruptive innovation in the disk drive industry (Christensen, 1997; Christensen et al., 1996). This binary variable monitors for changes in the system architecture as predicted by Hypothesis 2. This is a binary variable with a value of 0 if no changes are detected in the system architecture and 1 if changes in the architecture are observed.
- **Performance along Established Parameters (P_4 = 1 (Improved Performance), 0 (Same Performance), or -1 (Worse Performance)).** How does the performance of the product along established parameters change when the shift in

dominant design is observed? This parameter is measured differently by Tushman & Anderson (1986) and Christensen (1997). Tushman & Anderson (1986) identified key performance parameters in industries and mapped the % change in the most capable design each year. Discontinuities were identified as large changes in capabilities that were associated with changes in product design. Christensen mapped the average performance of all products in a given year to map performance or what he termed technological "capacity" (Christensen, 1993). Tushman & Anderson (1986) expected the performance to improve when a discontinuity occurs. Christensen (1993, 1997) expected performance to remain the same or get worse when a disruption occurs. This research measures the change in performance as an ordinal value (1, 0 or -1) by comparing the performance of the new dominant design to existing designs.

- **Performance along New Parameters (P_5 = 0 (Existing) or 1 (New)).** How does the performance of the product along new parameters change when the shift in dominant design is observed? Christensen (1997) argued that the basis of competition within an industry shifts as disruptive waves of innovations take place. Products that once competed on the basis of technological capacity (performance) now compete on the basis of size or quality and eventually will shift to competition based solely upon the basis of price as the product becomes a commodity. This variable is intended to detect this shift. If the new dominant design displays a significant change that improves performance along a new parameter, such as improved quality or reduced size and weight. then the variable will be given a value of 1. If no significant shift is noted, the variable is set to 0.

- **Cost Performance (P_6 = 1 (Higher Cost), 0 (Same Cost), or -1 (Lower Cost)).** How does the cost of the product change when the shift in dominant design is observed? Neither theory emphasizes cost. Christensen (1997) cited cost savings as potential new benefit to be gained but focuses on the impact of technical capacity exceeding market demand. Alternatively, Adner (2002: 684) pointed out that cost may be an important factor in disruption, "Customers with sufficiently satisfied functional requirements are more concerned with differences in absolute price than with differences in price/performance points." Tushman & Anderson (1986, 1990) did not cite cost as a factor in their theory. When Adner (2002) spoke of cost, it was from the perspective of the individual customer was defined as the price of the product to the customer. However, when companies are the customers of the innovation, as in the case of the Owens Automatic Bottling Machine (Anderson & Tushman, 1990), the purchase price does not represent the value that the company places on the purchase. It is the innovation's impact on the company's profits that are most important. This research measures the change in cost as an ordinal value (1, 0 or -1) by comparing the cost of the new dominant design to existing designs from the perspective of the design's customer.
- **Industry Migration (P_7 = a (Main), b (Low-End), or c (New)).** What industry did the new dominant design originate in? The theory of discontinuous innovation speaks directly to this variable, but in each of the examples used by Tushman & Anderson (1986, 1990), the innovation originated in the industry where the dominant design shift occurred. The theory of disruptive innovation

specifically cites low-end markets (Christensen, 1997) and new markets (Christensen & Raynor, 2003) as the original markets for disruptive innovations.

Data Handling Procedures

The data set to be analyzed is defined as an *N*-by-*P* matrix where *N* represents shifts in dominant design and *P* represents the variables P_1 through P_7 as shown in Equation (1).

$$N \text{ innovations} \overbrace{\begin{pmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} \\ \vdots & & & \vdots & & & \vdots \\ X_{n1} & X_{n2} & X_{n3} & X_{n4} & X_{n5} & X_{n6} & X_{n7} \end{pmatrix}}^{P \text{ variables}} \quad (1)$$

Sample Size. Sample size does not relate to statistical significance or statistical power in cluster analysis in the traditional sense of statistical inference (Everitt et al., 2001; Hair et al., 2006; Kaufman & Rousseeuw, 1990; Kettenring, 2006). "Cluster analysis has no statistical basis upon which to draw inferences from a sample to a population…Therefore, if possible, a cluster analysis should be applied from a confirmatory mode, using it to identify groups that already have established conceptual foundation for their existence" (Hair et al., 2006: 560). The theories of discontinuous and disruptive innovation provide the conceptual foundation of this research.

In order to test the usefulness of the theories of discontinuous and disruptive innovation, the research sample must be large enough to provide evidence of generalizability. The sample for this research does not need to be large. It is testing for the presence of two large clusters in the data field. Even 10 data points can be sufficient to test for the presence of two clusters. However, the size of the sample must be sufficiently large to complete the validity tests that will be discussed later.

While cluster analysis does not statistically infer relationships in the sample population (real world), it is possible to test a null hypothesis that the clusters formed are due to random variation in the data set – a kind of Type 1 error. This methodology will be discussed in the section on validity measures. Sample size does impact our ability to reject the null hypothesis that our clusters have formed from random variation and 100 data points proved sufficient to meet all the tests of validity required by this methodology.

Data Collection. Two data sets were collected. First, a small pilot data set was systematically selected from a population of dominant design shifts described in the literature. Half of the data points were drawn from the literature of discontinuous innovation and half from the literature of disruptive innovation. This first data set was used to test and refine this methodology with a known data set. The research sample data set was drawn from a simple random selection of 100 industries from the 1175 six-digit code industries classified in the 2007 North American Industrial Classification System. Archival analysis of industry literature from each of the 100 sampled industries was examined to identify candidate shifts in dominant design. For both data sets, the relevant data points for each variable (P_1 through P_7) were recorded as described earlier.

Procedures for Outliers. Hair et al. (2006) noted three potential reasons for the presence of outliers (objects that stand out from the remainder of the variate): (1) The data point may suffer from some sampling error and the data is suspect; (2) The data point may represent some small structure within the data; and (3) The data may represent a larger structure in the data population that is not well represented in the data sample for some reason. The data sample collected here was examined using standard univariate (histogram) and bivariate (scatterplot matrix) techniques prior to cluster analysis. The purpose of this review was to uncover any category (1) outliers. Outliers were noted but not removed in this first review.

When the cluster analysis was complete, the data sample was reviewed again for outliers that might be only be visible in a multivariate construct. At this point outliers were examined and separated from the data sample so that the cluster analysis could be run again in order to more clearly see the groups that are expected to represent discontinuous and disruptive innovations. Outliers that are not representative of the population should be deleted from the analysis (Hair et al., 2006). In every case, outliers were assessed to evaluate whether they represented category (1), (2), or (3) and are addressed in the conclusion of this analysis. These outliers proved to be a rich source for identifying potential avenues for future research.

> The deductive portion of a complete theory-building cycle can be completed by using the model to predict ex post what will be seen in other sets of historical data or to predict what will happen in the future. The primary purpose of the deductive half of the theory-building cycle is to seek anomalies, not avoid them. This is how theory is improved. (Christensen, 2006: 45)

Similarity and Dissimilarity. Similarity measures record the closeness between two objects and dissimilarity measures the distance between two objects. Both similarity and dissimilarity are measures of proximity. Similarity measures are typically used to measure categorical data and dissimilarity measures are typically used to measures continuous data (Kaufman et al., 1990). This research measures proximity of object i and j by the dissimilarity, $d(i, j)$.

This research analyzes three types of data: asymmetric binary data, ordinal data, and nominal data. Our measurements of new technology (P_1), core components (P_2), system architectures (P_3) and technological performance along new parameters (P_5) are used to represent aspects of the theories of discontinuous and disruptive innovation. The theory of discontinuous innovation emphasizes the presence of new technology and core components. The theory of disruptive innovation emphasizes the role of architectural innovation. The distinction between symmetric and asymmetric binary data is based upon whether one result is emphasized more than the other or whether each result is given equal weight (Gan, Ma, & Wu, 2007). Since our typology (See Table 10) does not give equal weight to the binary states of 1 and 0, our research will treat the variables P_1, P_2, P_3 and P_5 as asymmetric binary variables.

A well-known method for measuring the dissimilarity of asymmetric binary variables with a range of (0,1) is Jaccard's coefficient (Gan et al., 2007; Kaufman et al., 1990). This method is based upon a 2-by-2 contingency table that compares the binary variable results between two objects (See Figure 29).

The measures technological performance (P_4) and cost performance (P_6) used in this research are ordinal variables. This research will use a straightforward method of placing the ordinal values in rank order and transforming the data to a scale between (0,1). The dissimilarity of the resulting ordinal variables with be measured using the Manhattan method as recommended by Kaufman et al. (1990) in Figure 30.

The last remaining variable, Industry Migration (P_7), is a nominal variable with three possible states. In this case, dissimilarity is measured with the simple matching

FIGURE 29
Jaccard's Coefficient, $d(i,j)$ (Adapted from Kaufman et al., 1990)

		Object i 1	0	
Object j	1	a	b	$a+b$
	0	c	d	$c+d$
		$a+c$	$b+d$	

$$d(i,j) = \frac{b+c}{a+b+c}$$

FIGURE 30
Procedures for Transforming the Ordinal Variables P_4 and P_6 to Dissimilarity Coefficients (Adapted from Kaufman et al. (1990))

Convert each variable f to rank order 1 thru f

Compute the dissimilarity of the objects using a standardized Manhattan Distance

$$d_{ij}^{(f)} = \frac{\left| z_{i1} - z_{jf} \right|}{\text{Range of variable } f}$$

coefficient in Equation 2. Where P is the total number of variables and u is the number of variables that match between object i and j.

$$d(i,j) = \frac{P - u}{P} \qquad (2)$$

Proximity measures must be combined in order to estimate dissimilarity between objects with a data matrix of mixed variables – as in this research. Kaufman et al. (1990) provide a function for this purpose that is shown in Equation 3 and is the function that is used in this research to measure dissimilarity. It measures the proximity of the asymmetric binary variables (P_1, P_2, and P_3) with the Jaccard coefficient. It takes the ordinal variables (P_4 and P_6) that have been converted to a scale between 0 and 1 and their proximity will be measured with a Manhattan distance function as described in Figure 26. The final variable, P_7, is nominal and will be measured with a simple matching function of assigning 0 to the distance, $d_{ij}^{(f)}$, if the variables are identical and 1 if they are different.

$$d(i,j) = \frac{\Sigma_{f=1 \text{ to } p}\ \delta_{ij}^{(f)}\ d_{ij}^{(f)}}{\Sigma_{f=1 \text{ to } p}\ \delta_{ij}^{(f)}} \qquad (3)$$

Standardization. The scale represented by each variable has a large impact on the results of the cluster analysis (Kettenring, 2006). The asymmetric binary variables (P_1, P_2, P_3 and P_5), the ordinal variables (P_4 and P_6), and the nominal variable, P_7, are standardized on a scale from 0 to 1 by the proximity measures discussed in the last section. Therefore, special procedures for standardization are not required.

Assumptions in Cluster Analysis

The Sample is Representative of the Population. In order to ensure that clusters identified in this analysis have validity in describing the process of innovation in our industries, the research sample must be representative of the larger population. Discontinuous and disruptive innovations have been applied across many industries.

There are no industries identified in the literature where these theories would not have potential application. The main sample drawn in this research is a simple random selection of 100 industries from the 1175 six-digit code industries classified in the 2007 North American Industrial Classification System. The use of a random selection method ensures that the sample is representative of all industries classified in the 2007 North American Industrial Classification System.

Multicollinearity. Variables that exhibit multicollinearity can skew the results of cluster analysis. In these cases, the variables that are correlated will be more heavily weighted than those that are not since each variable is equally weighted in cluster analysis (Hair et al., 2006). A simple correlation analysis is conducted to determine if the extent of multicollinearity warrants the elimination of any variables from the cluster analysis.

Conduct the Cluster Analysis

Select the clustering algorithm. There are two general types of clustering algorithms – those that divide or partition data and those that arrange data into hierarchies. Partitioning methods do what the term partition implies. Data is clustered such that each object is assigned to one and only one group and each group has at least one object within it (Kaufman et al., 1990). Hierarchical methods create a tree like structure by either divisive or agglomerative methods (Kaufman et al., 1990). Divisive methods start with the entire data set and dividing groups of objects until the data set is divided into its component objects. Agglomerative methods start with all the individual objects and begin to clump similar objects together until the entire data set is recombined. Hierarchical methods are often displayed in trees or dendrograms.

Since the objective is to test the partitioning of our data into categories of disruptive and discontinuous innovation, a clustering by partition is the desired end result. Partitioning methods are further subdivided into hard and soft methods. Hard methods assume that that each object is assigned to one cluster or another. Soft methods such as fuzzy clustering methods allow for the possibility that clusters may overlap and individual objects may belong to both clusters. "The ability to describe such ambiguous situations is an important advantage of the fuzzy approach" (Kaufman et al., 1990: 43). This research employs the K-means fuzzy clustering methods implemented in the S-PLUS™ 7.0 for Windows software package. Theory predicts at least two predominant clusters (K= or > 2). K-means clustering assigns a membership coefficient for each data point to indicate the affinity of each data point with the clusters identified. This method of clustering is well suited to handling mixed data types (Jain et al., 1999).

Multiple cluster solutions will be tested (K=2,3, and 4) to determine which provides the best fit for the data sample. The normalized version of Dunn's coefficient and the highest average silhouette width each provide insight into what will be considered the best-fit solution. The normalized Dunn's coefficient measures the "fuzziness" of the clustering solution to the data on a scale of 0 (worst fit) to 1 (best fit) (Everitt et al., 2001; Kaufman et al., 1990). Cluster solutions with a normalized Dunn's coefficient near the value of 1 are very distinct. Each cluster is sharply defined. Silhouette width is used to measure the quality of any cluster analysis solution that partitions data. Silhouette widths measure the interobject dissimilarities within a cluster. Clusters with high silhouette widths (on a scale of 0 to 1) have less internal dissimilarity than clusters with low silhouette widths. The average silhouette width is an average of the silhouette widths of the cluster solution and is a standard measure of the overall quality of the partition solution (Kaufman et al., 1990). It is expected that the K= or > 2 solution will fit best if the theories of discontinuous and disruptive innovation account for the majority of the data. In the end, the validity of any clustering algorithm is tested by theoretical and external validity (Hair et al., 2006).

Cluster Interpretation and Validation

The interpretation of clusters normally involves analysis of the variable states represented in each cluster and identifying distinguishing characteristics (Hair et al., 2006). In this research, the expected relationship between the variables and the cluster solution is predicted in hypothesis 1, 2 and 3. It is expected that this research will develop a better understanding of the usefulness of the theories of discontinuous and disruptive innovation to describe the sample of design shifts collected and analyzed here. Strongly formed clusters (cluster solutions with a high Dunn coefficient) represent a high level of usefulness. Weak clusters indicate weaknesses in our source theories to distinguish shift in dominant design as either discontinuous or disruptive. It is possible that new clusters in the sample may be observed. In that case, the cluster solution will be compared to the theories of Chapter Two for possible explanation.

Several methods are used to check the cluster solution for validity. First, the sample set is randomly divided and each set is tested using the same clustering solution to validate the clusters for internal consistency (Hair et al., 2006). Second, a null data set is formed by randomly developing variables with a Monte Carlo approach – using similar characteristics to the sample data set (Aldenderfer et al., 1984). The clustering procedure used on the sample set is then be used on the Monte Carlo data set to compare the quality

(Dunn coefficient and silhouette values) of the research cluster result with a data set known to be random. Third, Fisher's exact test is used to compare the statistical significance of the clusters formed compared to the random Monte Carlo data sets. The final test of validity is whether there is external, theoretical validity for the solutions found. Do clusters form as predicted by hypotheses 1, 2, and 3? Do new clusters formed that are not explained in the research?

ANALYSIS OF DATA AND RESULTS

A Pilot Study of the Proposed Methodology

The pilot study tests the ability of the cluster analysis methodology described in the previous section to distinguish between shifts in dominant design that have been classified as discontinuous or disruptive by prior research. The results of the pilot study presented here both validate the procedures outlined in the previous section and build confidence in the methodology's ability to test the proposed typology with a larger randomly sampled data set.

Data Collections Procedures for the Pilot Study. Ten innovations were systematically chosen to form a data set for this pilot study. Five innovations were chosen to represent shifts in dominant design from the literature of discontinuous innovation. A similar set of five innovations were chosen from the literature of disruptive innovation. In total, the ten innovations chosen represent empirical data drawn from existing theory and represent ten very different industries (See Table 11).

The data collection protocol established in the preceding section was used to code each shift in dominant design and its associated innovations according to the variables, P_1 through P_7 (See Table 12). Additional data was sought from industry trade journals and other available archival data as necessary. Summary descriptions of each of these shifts in dominant design are contained in Appendix B.

Pilot Study Results. One outlier was noted when the pilot data set was examined using univariate (histogram) analysis. The data point, D_5 (Radial Automobile Tires) is an outlier as the only data point in the pilot data set where cost, P_6, increases. Radial tires

TABLE 11
Pilot Study Innovation Design Shifts

Type of Innovation	Old Design	New Design	Reference
Discontinuous Innovations	Packard Bell 250 12 Bit, hybrid analog/digital computer, transistors	DEC PDP-8 16 Bit minicomputer, core memory, integrated circuits	Anderson & Tushman (1990)
	Douglass DC-7C	Boeing 707-120 Aircraft	Anderson & Tushman (1990)
	Hand Blown Glass	AN/AR Series Owens Machine Bottle Manufacture	Anderson & Tushman (1990)
	Group 2 Analog Fax Machines	Group 3 Digital Fax Machines	Coopersmith (1993)
	Bias Ply Automobile Tires	Radial Automobile Tires	Sull et al. (1997)
Disruptive Innovations	Laser Jet Printers	HP Thinkjet	Christensen (1997)
	Integrated Steel Mill	Steel Minimill	Christensen (1997)
	8 inch Hard Disk Drive	5.25 inch Hard Disk Drive	Christensen & Bower (1996)
	Cardiac Bypass Surgery	Balloon Angioplasty	Christensen & Raynor (2003)
	Full Service Brokers	Internet Stock Brokers	Claude-Gaudillat & Quélin (2006)

TABLE 12
Pilot Study Data Table

Discontinuous Innovation	New Dominant Design	P_1 New Technology	P_2 New Core Component	P_3 New System Architecture	P_4 Performance along Established Parameters	P_5 Performance along New Parameters	P_6 Cost	P_7 Industry Migration
1	DEC PDP-8	1	1	1	1	1	-1	c
2	Boeing 707-120 Aircraft	1	1	0	1	0	-1	a
3	AN/AR Series Owens Machine	1	1	1	1	0	-1	a
4	Group 3 Digital Fax Machines	1	1	0	1	0	-1	a
5	Radial Automobile Tires	1	1	1	1	0	1	a
Disruptive Innovation								
6	HP Thinkjet	1	1	1	-1	1	-1	c
7	Steel Minimills	0	1	1	0	1	-1	b
8	5.25 inch Hard Disk Drive	0	1	1	-1	1	-1	b
9	Balloon Angioplasty	1	1	1	0	1	-1	c
10	Internet Stock Brokers	0	1	1	-1	1	-1	b

cost 30- 50% more than bias ply tires, and their longer life translates to a lower cost per mile basis with less trips to tire dealers for replacements (Sull et al, 1997). This is reflected in the data set as an increase in expected performance ($P_4 = 1$) while the cost also increases ($P_6 = 1$). Radial tires represent a category 2 or 3 outlier (representative of a subset underrepresented in the pilot study). It will be removed from analysis so as not to dilute the cluster analysis of the remaining nine data points. This category (P_4=1, P_6=1) will be examined again in the full data set.

Excluding data point D_5 (as noted in the above paragraph), the variables for changes in core components (P_2) and cost (P_6) show no variability across the pilot data set. To include these variables in the cluster analysis would dilute the ability of cluster analysis to form data clusters from the remaining variables (Hair et al., 2006). These two variables are removed from the cluster analysis of the pilot data set. The data set was also examined with bivariate (scatterplot) analysis; however, with so few data points, no conclusions were drawn.

The pilot study data table was examined for multicollinearity. Although there are few data points in this sample, there was a strong correlation between new systems architectures (P_3) and the advance of system performance along new parameters (P_5). It is conceivable that these two variables are linked since new parameters such as reduced size or improved quality often require new system architectures. When two variables in a cluster analysis are interrelated, they exert an undue influence on the result of the analysis (Hair et al., 2006). Since it is desired that each variable exert the same influence in this analysis, the variable P_3 was excluded from pilot test cluster analysis. A dissimilarity matrix was constructed (Table 13) and analyzed using the algorithms, DAISY and

TABLE 13
Pilot Study Dissimilarity Matrix

Data Set	1	2	3	4	5	6	7	8	9	10
1	**X**	0.5	0.5	0.5	X	0.25	0.625	0.75	0.125	0.75
2	1	**X**	0	0	X	0.75	0.875	1	0.625	1
3	2	9	**X**	0	X	0.75	0.875	1	0.625	1
4	3	10	16	**X**	X	0.75	0.875	1	0.625	1
5	X	X	X	X	**X**	X	X	X	X	X
6	4	11	17	22	X	**X**	0.625	0.5	0.125	0.5
7	5	12	18	23	X	27	**X**	0.167	0.5	0.167
8	6	13	19	24	X	28	31	**X**	0.625	0
9	7	14	20	25	X	29	32	34	**X**	0.625
10	8	15	21	26	X	30	33	35	36	**X**

FANNY, implemented in S-PLUS^{tm} 8.0 for Windows (Note that D_5 was not included in the analysis). Potential two and three cluster solutions were considered (See Table 14). The high average silhouette width of the three cluster solution (>0.5) indicates strong data structure and suggests high confidence in the three cluster solution (Kaufman et al., 1990). Values of $k > 3$ were not explored since the FANNY clustering algorithm does not allow clustering at k values greater than or equal to N/2.

The remaining pilot study variables (P_1, P_4, P_5, and P_7) were examined to evaluate their ability to discriminate across the two and three cluster solution. The three cluster solution shown in Table 14 was chosen as the best representation of the data for testing the research hypotheses.

Figures 31 and 32 illustrate the three cluster solution using silhouette widths and a projection of the first two components of a primary component analysis onto two

TABLE 14
Cluster Analysis Results (Pilot Study)

Number of Clusters (k)	Dunn's Coefficient Normalized	Average Silhouette Width
k = 2	0.555	0.515
k = 3	0.784	0.835

dimensions. Table 15 shows the membership coefficients for each data point in the k=3 cluster solution.

Pilot Study Discussion. The pilot study correctly identified 8 of 9 data points and confirms the ability of this research methodology to test the ability of the proposed taxonomy to integrate theories of discontinuous and disruptive innovation. The three cluster solution generated by the methodology displays both internal and external validity. This small data set is too small to split in half to test for methodological reliability in the formation of the clusters as suggested by Hair, et al. (2006). The pilot study three cluster solution was compared with a Monte Carlo data set with the same overall statistical distribution as the pilot study data set variables (Aldenderfer et al., 1984). The frequencies of the data sets within each cluster solution was compared to the Monte Carlo data set with Fisher's exact test to test the statistical significance of the data within each cluster. External validity was tested by comparing the three cluster pilot test solution with the original source research that identifies data points 1, 2, 3, 4, and 5 with discontinuous innovation and data points 6, 7, 8, 9, and 10 with disruptive (See Figure 33).

FIGURE 31
Silhouette Plot of the Pilot Study Three Cluster Solution

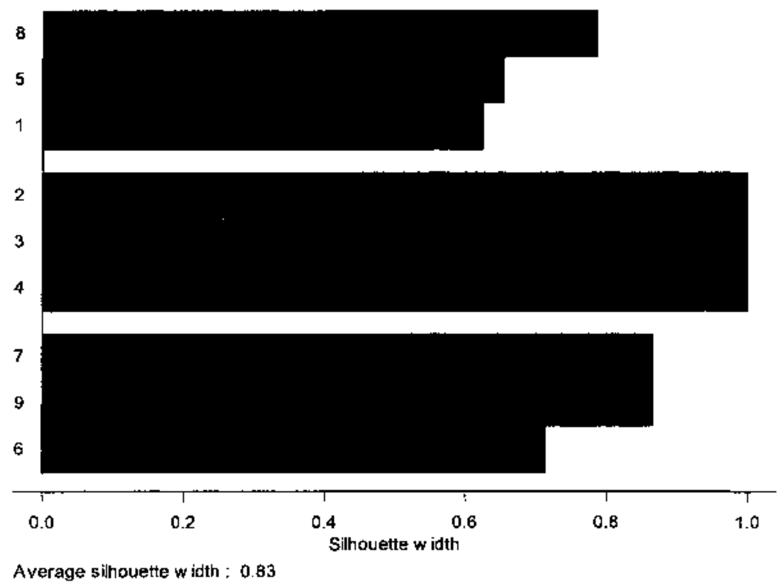


FIGURE 32
Two Dimension Representation of the Pilot Study Three Cluster Solution

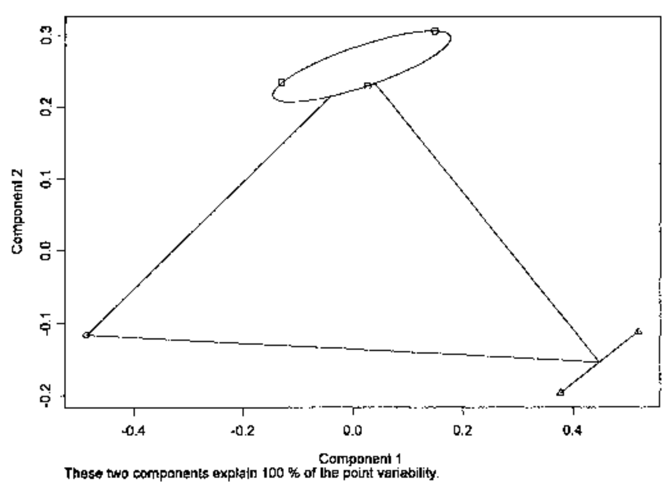


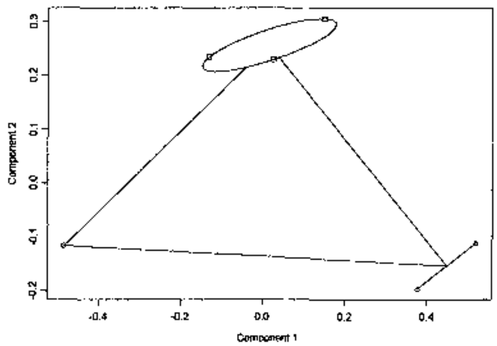
TABLE 15
Membership Coefficients of the Pilot Study Three Cluster Solution

Innovation Data Set	Cluster One Membership Coefficient	Cluster Two Membership Coefficient	Cluster Three Membership Coefficient
1	0.79	0.12	0.09
6	0.80	0.08	0.12
9	0.93	0.03	0.04
2	0	1.00	0
3	0	1.00	0
4	0	1.00	0
7	0.14	0.09	0.77
8	0.02	0.01	0.97
10	0.02	0.01	0.97

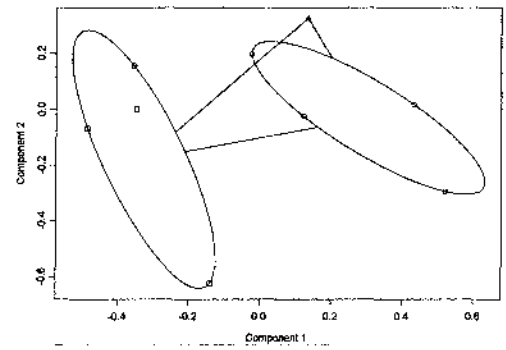
The pilot study fuzzy three cluster solution displays internal validity as compared to the Monte Carlo solution. The values of Dunn's coefficient normalized, and the average silhouette width of the fuzzy three cluster solution are significantly greater than the Monte Carlo solution. The data sets that form the three cluster solution are statistically significant ($p = .07$) as compared to the random Monte Carlo data set with Fisher's exact test. The power of this test is limited by the small sample size ($n=9$).

External validity is corroborated by noting that with the exception of data point 1, the three clusters agree with expected theoretical result. Cluster two contains data points 2, 3 and 4 – all previously identified as discontinuous innovations. Cluster one contains data points 1, 6, and 9 – data points 6 and 9 are previously identified as disruptive innovations that created new markets. Cluster three contains data points 7, 8, and 9 – all previously identified as disruptive innovations that first started in low end markets.

FIGURE 33
Comparison of the Pilot Study Three Cluster Solution with a Monte Carlo Three Cluster Solution



Pilot Study Three Cluster Solution



Monte Carlo Three Cluster Solution

Solution	Dunn's Coefficient Normalized	Average Silhouette Width
Pilot Study Three Cluster	0.784	0.835
Monte Carlo Three Cluster	0.331	0.322

Data point 1 is the exception that proves the rule. Anderson & Tushman (1990) identified the PDP-8 as a discontinuous innovation because it is one of the first minicomputers to introduce the integrated circuit. Voelcker (1988), however, pointed out that customers valued the PDP-8 because of its reliability, reduced size and reduced cost. A big factor in both the increase reliability and reduced cost was DEC's introduction of an automated wire wrapping production process that eliminated the need for hand assembly. The PDP-8 was introduced directly into the new minicomputer industry. However, Voelcker (1988) also noted that the real popularity for the minicomputer came because it was appropriating customers who could not afford the low end of the mainframe market whose computers costs hundreds of thousands of dollars. The use of an automated wire wrapping process to achieve a smaller and more economical architecture is a characteristic typical of a disruptive innovation. The appeal of the new DEC PDP-8 to a new market of customers that previously could not afford minicomputers is a characteristic similar to disruptive innovation. The DEC PDP-8 shares more characteristics of disruptive innovations than discontinuous innovations while having some characteristics of both.

Analysis of the Research Sample

This section presents the results of analysis performed on a random selection of innovations from across a broad spectrum of industries to test the typology constructed by this research. In the first result, the presence of disruptive innovation could not be distinguished from outliers removed to improve the cluster analysis. This required the development of dummy variables to amplify the signal of disruptive innovation within the data set and a second analysis of the data. This section describes and discusses the results of both analyses.

Analysis of the First Research Data Set

Data Collections Procedures for the First Research Data Set. The research data set was drawn from a simple random selection of 100 industries from the 1175 six-digit code industries classified in the 2007 North American Industrial Classification System. Archival analysis of industry literature from each of the 100 sampled industries was examined to identify candidate shifts in dominant design. For both data sets, the relevant data points for each variable (P_1 through P_7) were recorded as described earlier.

The data collection protocol established in the preceding section was used to code each shift in dominant design and its associated innovations according to the variables, P_1

through P_7. Additional data was sought from the *Encyclopedia of American Industries* (Pearce, 2005), industry trade journals and other available archival data.

Univariate Analysis of the First Research Data Set. Histograms were constructed and reviewed for outliers as recommended by Hair et al. (2006). As before, if the review revealed a category (1) error, then the data set was corrected and the analysis repeated. Two outliers were noted in the P_2 (Core Component) variable set. Two data points were noted where no significant dominant shift have occurred. The delivery of heating oil has not significantly changed since the oil fired furnaces became a common means of heating the home. Additionally, the invention of the telephone book followed quickly the invention of the telephone and has not significantly changed throughout the last century. These data points were treated as category (2) outliers and identified for later removal and are discussed later in the results. With the exceptions of the two outliers just noted, the variable P_2 did not change across the data set. This variable was later removed from the cluster analysis as recommended by Hair et al. (2006) in order to minimize diluting the effects of the remaining variables. In the pilot data set, it was noted that the variable P_6 (Cost) did not vary across the pilot sample set. In the research data set, 36% of the data points showed an increase in cost. The variable P_6 will be included in the cluster analysis of the research sample.

Only three instances of new market innovations (P_7 = c) were noted in the data set. This was treated as a category (3) outlier. The body of research on disruptive innovation has highlighted many instances of new market innovations. Under representation of this subset is not considered significant since a sufficiently large number of low end innovations (P_7 = b) are present and will serve to represent the theory of disruptive innovation in the data set. These data points were not removed since the value of observing how these data points were clustered outweighed any concern that these outliers might dilute the remaining data set.

Bivariate Analysis of the First Research Data Set. The scatter plot shown in Figure 34 was constructed and reviewed as recommend by Hair et al. (2006). All bivariate combinations that represented 5 or less data points in the research data points were examined as outliers. As before, if a category (1) error was noted, it was corrected and the scatterplot analysis was re-performed. Twenty one data points were identified as outliers. Eighteen data points were removed from further analysis as category (2) outliers that were representative of small subsets in the research population that were not critical to the research objectives. The three data points with P_7 (Market) = c were included in the cluster solution as recommended by Hair et al. (2006) since they are likely to represent valid groups in the cluster analysis. The outliers that were removed are circled on the scatterplot shown in Figure 35.

The remaining data set was examined for multicollinearity as recommended by Hair et al. (2006). A correlation matrix (see Table 16) of the six remaining variables across 82 remaining data points reveals a strong correlation between P_4 (Cost) and P_7 (Market) that was not obvious in the scattergram analysis. Correlations in the data suggest that there is an underlying structure. Correlations of greater than or equal to 0.26 are statistically significant ($p<.01$). A preliminary cluster analysis was conducted comparing the results with P_7 (Market) included and excluded. The inclusion of P_7 did not significantly alter the results. Since P_7 (Market) is a highlighted feature of the

FIGURE 34
Scatterplot of the First Research Data Set

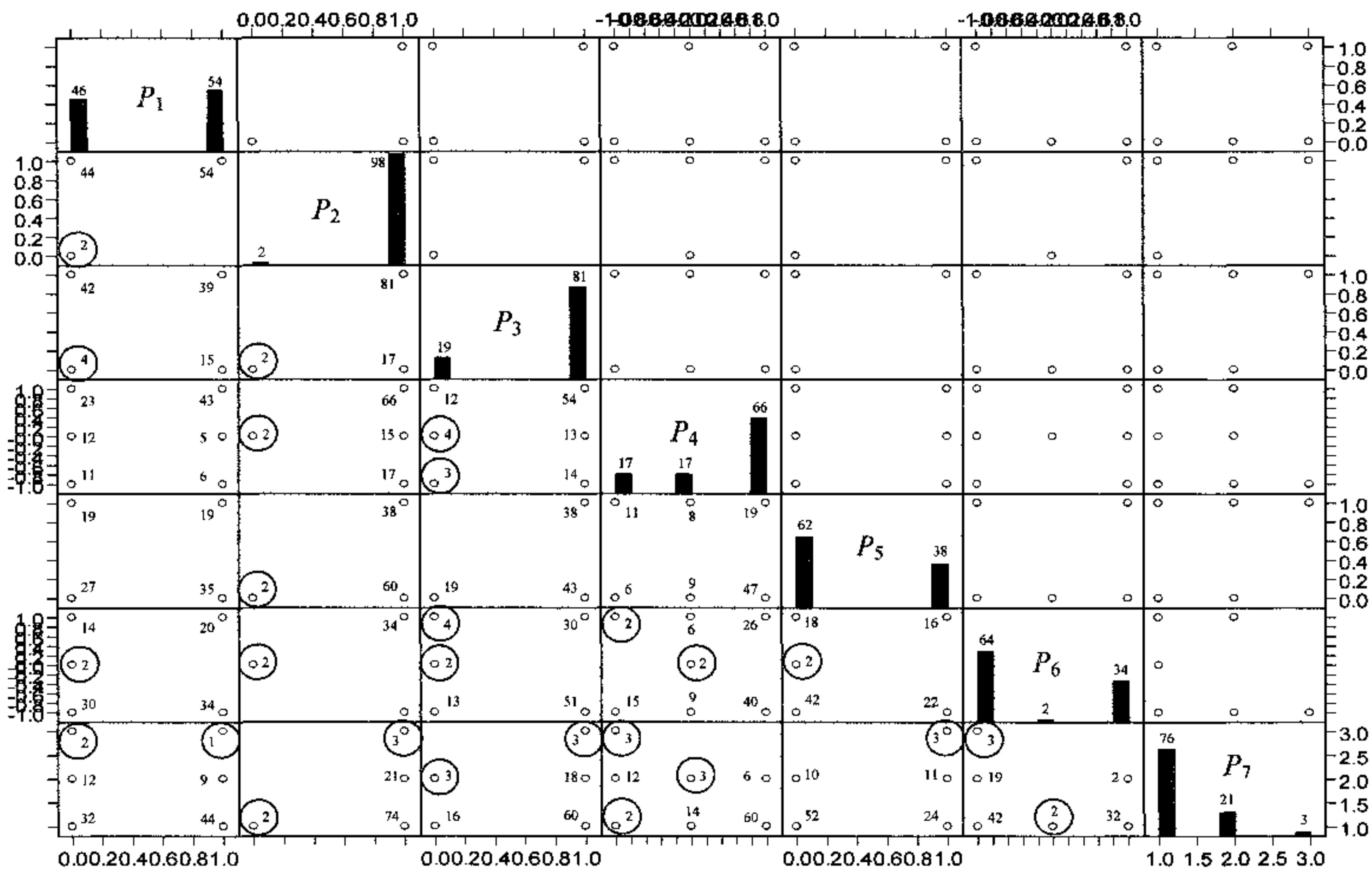


TABLE 16
Correlation Matrix of the First Research Data Set

	P_1	P_3	P_4	P_5	P_6	P_7
P_1	1.00					
P_3	**-0.28**	1.00				
P_4	**0.31**	-0.17	1.00			
P_5	-0.04	**0.26**	**-0.35**	1.00		
P_6	0.03	0.21	0.18	0.13	1.00	
P_7	-0.16	0.14	**-0.74**	**0.34**	**-0.32**	1.00

disruptive theory, it was left in the analysis – recognizing that it would likely enhance the presence of disruptive innovation in the final cluster result.

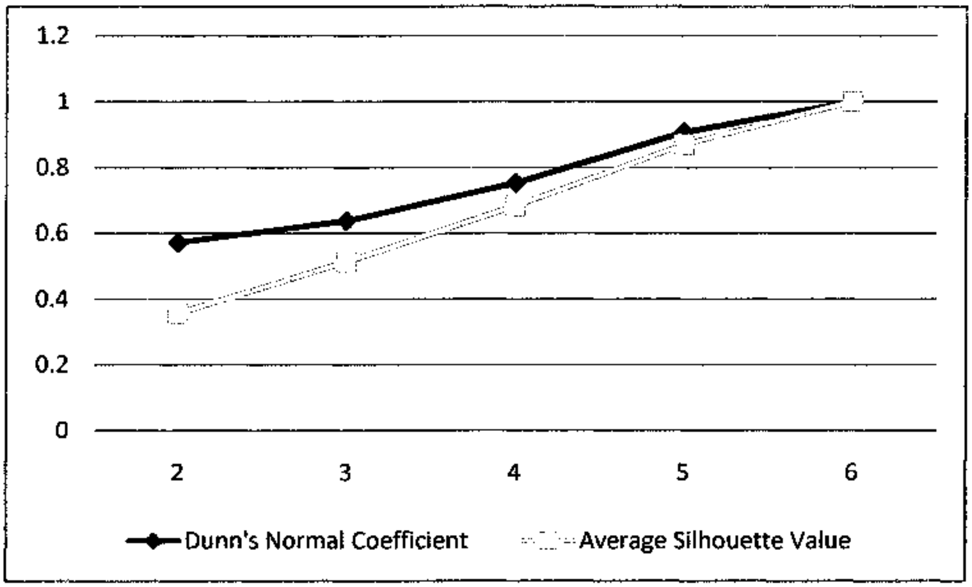
Several of the subsets of data in Table 17 are the equivalent of multivariate outliers. 15 of the 21 subsets number five or less in number. With the removal of the multivariate outliers, the variables P_4 (Performance) and P_7 (Market) no longer vary across the variate and were removed from the resulting cluster analysis. The final research data set used in the cluster analysis (47 data points, 4 variables) is shown in Table 17.

Cluster Analysis of the First Research Data Set. With the removal of more than half the data points, a cluster analysis is not required to see the remaining data structure. However, for methodological completeness, a cluster analysis and the necessary validity checks were conducted prior to assessing the results of this first iteration. A dissimilarity matrix was constructed and analyzed using the algorithms, DAISY and FANNY, implemented in S-PLUS^{tm} 8.0 for Windows. Multiple cluster solutions were generated as shown in Figure 35. Every cluster generated resembled discontinuous innovation. Therefore, the cluster solution that most closely fit the hypothesis was the k = 1 solution. The entire research sample (with outliers removed) is a discontinuous cluster.

TABLE 17
First Research Data Set (All Data Points)

Number of Data Points	P_1 New Technology	P_2 New Core Component	P_3 New System Architecture	P_4 Performance along Established Parameters	P_5 Performance along New Parameters	P_6 Cost	P_7 Industry Migration
12	1	1	1	1	0	-1	a
8	0	1	1	1	0	-1	a
7	0	1	1	1	0	1	a
7	1	1	0	1	0	-1	a
7	1	1	1	1	1	1	a
6	1	1	1	1	0	1	a
Outliers Removed During Multivariate Analysis							
5	0	1	1	1	1	-1	a
4	0	1	1	0	1	1	a
4	0	1	1	-1	1	-1	b
3	1	1	1	1	1	-1	a
3	0	1	1	0	0	-1	a
3	0	1	1	-1	0	-1	b
2	1	1	1	1	1	-1	b
2	1	1	1	0	1	1	a
2	1	1	1	-1	1	-1	b
2	0	1	1	-1	1	-1	c
1	1	1	1	1	0	-1	b
1	1	1	1	0	1	-1	a
1	0	1	1	1	1	1	a
1	0	1	1	1	1	-1	b
1	1	1	1	-1	1	-1	c
Outliers Removed During Univariate and Bivariate Analysis							
3	1	1	0	1	0	1	a
2	0	1	1	0	0	-1	b
2	0	0	0	0	0	0	a
2	1	1	0	0	0	-1	a
1	0	1	0	-1	0	-1	b
1	1	1	1	-1	1	1	b
1	1	1	1	1	0	1	b
1	1	1	0	-1	0	-1	b
1	0	1	1	-1	1	1	a
1	0	1	0	1	0	1	a
1	0	1	1	0	1	-1	b
1	1	1	0	1	0	-1	b
1	1	1	0	-1	0	-1	a

FIGURE 35
Cluster Analysis Results of the First Research Data Set



Number of Clusters (k)	Dunn's Coefficient Normalized	Average Silhouette Width
k = 2	0.57	0.36
k = 3	0.65	0.51
k = 4	0.75	0.68
k = 5	0.91	0.87
k = 6	1.00	1.00

Single Cluster Solution							
Number of Data Points	P_1 New Technology	P_2 New Core Component	P_3 New System Architecture	P_4 Performance along Established Parameters	P_5 Performance along New Parameters	P_6 Cost	P_7 Industry Migration
12	1	1	1	1	0	-1	a
8	0	1	1	1	0	-1	a
7	1	1	0	1	0	-1	a
7	0	1	1	1	0	1	a
7	1	1	1	1	1	1	a
6	1	1	1	1	0	1	a

Hypotheses Testing of the First Research Data Set

Hypothesis 1. *There is no natural grouping of discontinuous innovations where a new technology is introduced into a products core and results in a new dominant design that significantly outperforms previous designs along established performance parameters while competing in the main market of an industry.* The entire first research data set (after outliers are removed) has at least three of the four predicted characteristics of discontinuous innovation and 68% of the research sample displays all four of the predicted characteristics. The first research data set as a whole is a cluster of discontinuous shifts in dominant design. The null of hypothesis 1 is rejected.

Hypothesis 1a. *If a natural grouping of discontinuous innovations is present, the introduction of new technology is not a necessary component.* 15 of the 47 data points in the discontinuous cluster (first research data set) did not require a new technology (P_1 = 0) to achieve the dominant design shift. This hypothesis cannot be rejected.

Hypothesis 1b. *If a natural grouping of discontinuous innovations is present, the introduction of a new core component is not a necessary component.* All 47 data points in the discontinuous cluster (first research data set) included thc introduction of a new core component. This hypothesis is rejected. However, 98 of the original 100 data points collected displayed a new core component as a part of the change in dominant design. The two data points that did not have a change in core component, did not display design shifts. Therefore, while the hypothesis as stated is rejected, it appears that all shifts in dominant design require the introduction of new core components and that this characteristic is not unique to discontinuous innovation.

Hypothesis 1c. *If a natural grouping of discontinuous innovations is present, the improvement of performance along established trajectories is not a necessary component.* All 47 data points in the discontinuous cluster (first research data set) included the improvement of performance along established parameters ($P_4 = 1$). This hypothesis is rejected.

Hypothesis 1d. *If a natural grouping of discontinuous innovations is present, the introduction of the new dominant design within the main market of the industry is not a necessary component.* All 47 data points in the discontinuous cluster (first research data set) introduced the dominant design shift in the main market of the industry (P_7 = a). This hypothesis is rejected.

Hypothesis 2 and 3. Since all of the data in the research sample (excluding the outliers) is part of the discontinuous cluster, there is no data remaining to reject either hypothesis 2 or 3. This, in itself, is an interesting result. It first suggests that examples of discontinuous innovation are well established and occur frequently. It further indicates that if disruptive innovation is present in this data set, that its presence may be hidden by variation within the variables sampled. Disruptive innovation appeared to be an outlier. The 53 data points that have been classified as outliers are explored further after a discussion of the first research data set results.

Discussion of the First Research Data Set Analysis Results

First and foremost, a cluster was found within the 100 data points collected that corresponds to the theory of discontinuous innovation. The design shifts represented within the discontinuous cluster are shown in Appendix C. The data is organized into the six subsets identified in the cluster analysis. Further, the data structure within the discontinuous cluster raises some questions as to the role of the variables new technology (P_1), changes in core components (P_2), and the role of changes in design cost (P_7) within the theory of discontinuous innovation.

The discontinuous cluster can be separated into two subsets in order to examine the role of new technology (P_1) in these shifts in dominant design. The first subset (P_1=1) includes shifts in dominant design such as the shift from silk stockings to nylon stockings in the sheer hosiery industry (Hounshell & Smith, 1988) or the shift from a distributor to electronic ignition in the gasoline engine industry (McKay, 2008). In these subsets, new technologies placed an important role in the new dominant design. The second subset (P_1=0) includes the shift from day parks to theme parks in the amusement park industry (Adams, 1991) or the replacement of wild crayfish capture with crayfish aquaculture (farming) in the shellfish fishing industry (McClain & Romaire, 2004). In this second subset of design shifts, the emergence of new dominant designs did not require new technologies – just the application of existing technologies in new ways. This suggests that while new technologies can be useful in the creation of discontinuous design shifts, not all discontinuous design shifts require the introduction of new technology.

All data points within the discontinuous cluster exhibited changes in their core components (P_2=1). However, as discussed earlier in the univariate analysis, 98 of the 100 data points collected showed changes in their core technology. This suggests one of two possibilities. First, this variable may not be defined well. This is a relatively crude methodology that is only looking for gross effects within the variate. It is possible that the binary variable (P_2) did not account for variations in the amount of change of core components that is significant in distinguishing categories of innovation. Second, this variable may be correlated with the shift in dominant design. Not all innovations result in shifts of dominant designs; however, in this research, we have created a typology for the purpose of integrating theories that predict shifts in dominant design. Therefore, it is possible that all shifts in dominant design exhibit new core components. This is further substantiated by the fact that the only two data points that did not exhibit changes in their core components were in industries that displayed no significant shifts in their dominant designs.

The discontinuous cluster can be separated into two subsets in order to examine the role of cost (P_6) in these shifts in dominant design. The first subset ($P_6 = 1$) includes shifts in dominant design such as the shift from paper milk cartons to high density polyethylene (HDPE) milk cartons in the non-folding sanitary food containers manufacturing industry (Unknown, 1989) or the shift from non-standardized computer training to the development of IT certificates in the computer training industry (Haimson & VanNoy, 2004). This subset of discontinuous innovation acts as the models that Adner & Levinthal (2001) predict as users are willing to pay for product or process improvement. The second subset ($P_6 = -1$) includes the shift from using oil based color inks to soy based color inks in the printing of newspapers (Lustig, 2004) or the replacement of low temperature long time (LTST) pasteurization with high temperature short time (HTST) pasteurization in the dairy cattle and milk production industry (Dicker & Wiles, 1978). In this second subset of design shifts, the emergence of new dominant designs both improved product performance and reduced the cost to the user of the innovation. Adner & Levinthal (2001:612) suggested that once customers are "technologically satisfied" designs tend to converge at a stable price point. This second subset of discontinuous innovations seems to represent new dominant designs that find ways to deliver superior performance below the existing price points.

The results of these first tests suggest that discontinuous innovation is perhaps the most frequent cause of shifts in dominant design. When pursuing discontinuous innovation as a means of creating new dominant designs within industries, engineering and technology managers should pay close attention to the relationship between performance (P_4) and cost (P_6) in their designs. When there is sufficient unmet customer demand, customers will pay more for the design ($P_4 = 1$, $P_6 = -1$). Second, regardless of customer demand, if a new design can deliver superior performance at reduced cost, then the design is likely to create a shift in the industry's dominant design ($P_4 = 1$, $P_6 = -1$).

Much of the literature focuses on the ability of new technologies (P1 = 1) to enable improvement in performance. These results indicate that architectural innovation may provide an untapped resource for engineering and technology managers seeking improved performance in their designs. For example, Adams (1991) notes that Walt Disney tapped into unmet customer need for a family vacation destination when he designed the Disney theme park. Far different from the existing dominant design of day amusement parks that were collocated within the mass transportation hub of major cities, theme parks offered a place for families to spend several days. Disney used the excitement of Disney marketing power to capitalize on the existing popularity of Disney movies and the new *Wonderful World of Disney* television show, to build Disney themes into his new park. In total, when it first opened, a day at a Disney park cost twice what a family expected to pay at a day park, but they kept coming (Gillette, 1956).

The outliers in this research sample were combinations of variables that occurred 5 times or less within the data set. In total, removal of outliers resulted in excluding 53 of the original 100 data points. Additionally, if disruptive innovation is present in this data set, it is being excluded as an outlier. As a result, this first analysis of the research sample was unable to test hypotheses 2 and 3. The large number of outliers in the data set suggests significantly more variety and less grouping within the data sample than was observed in the pilot sample. This level of variety is not predicted by the theories of discontinuous or disruptive innovation and suggests that further research is needed to understand how best to characterize these results.

The theory of disruptive innovation (Hypothesis 2) has several conditional statements which are drawn from the theory of disruptive innovation. New dominant designs may equal or underperform existing designs along established parameters. This suggests that the value for performance along established parameters (P_4) could have either a value of 0 or -1. Disruptive innovations can display either new performance parameters ($P_5 = 1$) or reduced cost ($P_6 = -1$). Also, disruptive innovations are initiated by competing in low end markets ($P_7 = \text{b}$) or new markets ($P_7 = \text{c}$).

It was possible that the presence of disruptive shifts in dominant designs was being masked by the conditional nature of the theory. The presence of disruptive innovation was tested by recoding the research sample results with dummy variables to amplify the methodology's ability to distinguish disruptive innovation. This also required recombination of the P_5 and P_6 variables into a single variable, D_{56}. In this new coding scheme, disruptive innovation was expected to require new architectural design ($P_3 = 1$), exhibit equal or underperform existing designs ($D_4 = 0$), shift competition to

Table 18
Conversion Rules for Disruptive Dummy Variables

Original Variable	Dummy Variable
If P_4 = 0 or -1	Then set D_4 = 0
If P_4 = 1	Then set D_4 = 1
If either P_5 = 1 or P_6 = -1	Then set D_{56} = 1
If neither P_5 =1 or P_6 = -1	Then set D_{56} = 0
If P_7 = a	Then set D_7 = a
If P_7 = b or c	Then set D_7 = b

new parameters or reduce cost (D_{56} = 1), and initiate competition in a low end or new market (D_7 = b). This also has the effect of converting P_4 and P_6 into binary data. Hypothesis 2 and 3 remain as previously stated. A second research data set was created by coding the 100 data points of the research sample as defined in Table 18 and the methodology was repeated.

Three new sets of hypotheses were also created to test the second research data set. The hypotheses mirror the original hypotheses and will be used to test the research data set that incorporates the new dummy variables.

Hypothesis 4. *There is no natural grouping of discontinuous innovations where a new technology is introduced into a product's core and results in a new dominant design that significantly outperforms previous designs along established performance parameters while competing in the main market of an industry.*

Hypothesis 4a. *If a natural grouping of discontinuous innovations is present, the introduction of new technology is not a necessary component.*

Hypothesis 4b. *If a natural grouping of discontinuous innovations is present, the introduction of a new core component is not a necessary component.*

Hypothesis 4c. *If a natural grouping of discontinuous innovations is present, the improvement of performance along established trajectories is not a necessary component.*

Hypothesis 4d. *If a natural grouping of discontinuous innovations is present, the introduction of the new dominant design within the main market of the industry is not a necessary component.*

Hypothesis 5. *There is no natural grouping of disruptive innovations where a new architecture is introduced that results in a new dominant design that equals or underperforms existing designs along established parameters while shifting competition to new performance parameters (such as size or reliability) or reducing cost while competing in the low end or from an adjacent market of an industry.*

Hypothesis 5a. *If a natural grouping of disruptive innovations is present, the introduction of a new architecture is not a necessary component.*

Hypothesis 5b. *If a natural grouping of disruptive innovations is present, the presence of a dominant design that equals or underperforms existing designs along established parameters is not a necessary condition.*

Hypothesis 5c. *If a natural grouping of disruptive innovations is present, the improvement of performance along new parameters or the reduction in cost is not a necessary component.*

TABLE 19
Integrated Typology for Classifying Shifts in Dominant Design with Dummy Variables

Dimensions of Typology		Interdependent Variables	Discontinuous Innovation	Disruptive Innovation
Locus of Innovation	Component	New Technology Introduced (P_1)	Yes	
	Component	Core Component Change (P_2)	Yes	
	System Architecture	System Architecture Change (P_3)		Yes
Product Utility	Performance	Product Performance along Establish Parameters (D_4)	Better	Same or Worse
	Performance	Customer Shift in Established Parameters or Reduced Cost (D_{56})		Yes
Market	Existing	Where was the New Product Introduced? (D_7)	Main Industry	Low-end or New Market

Hypothesis 5d. *If a natural grouping of disruptive innovation is present, the introduction of the new dominant design in the low end of existing markets or within adjacent markets is not a necessary component.*

Hypothesis 6. *A taxonomy constructed from shifts observed in the dominant design of an established industry does not display natural clusters of innovation as predicted by the typology (Table 19) constructed from the theories of discontinuous innovation and disruptive innovation.*

Validity of First Research Sample Results

The reliability of the first research sample results was tested by randomly splitting the variate into two groups and testing the resulting cluster solution for internal consistency as recommend by Hair et al. (2006). The cluster solutions of the two groups were identical. This, of course, is not surprising since the entire variate was the solution cluster. A series of five random data sets were constructed with a Monte Carlo approach taking care to ensure that each variable in the randomly constructed variates displayed characteristics similar to the research sample as recommend by Aldenderfer et al. (1984). With a k=1 solution, it is not possible to calculate Dunn's normal coefficient or the average silhouette width to compare with the Monte Carlo solution. Using Fisher's exact test, the data sets in the single cluster solution occur more frequently than the same data sets as averaged across five random sample groups ($p<0.01$). The external validity of the research sample was established with the rejection of the null for hypothesis 1.

Analysis of the Second Research Data Set (w/Dummy Variables)

A second research sample was developed using the coding system shown in Table 18. The resulting research data set (w/dummy variables) was analyzed using the methodology discussed earlier. Hypothesis 4, 5, and 6 were created to distinguish between the tests conducted in the first analysis of the research sample and tests conducted in the second analysis. These hypotheses directly correspond to the original three hypotheses without modification.

Univariate Analysis of the Second Research Data Set (w/Dummy Variables). Histograms were constructed and reviewed for outliers as recommended by Hair et al. (2006). As before, two outliers were noted in the P_2 (Core Technology) variable. These data points were treated as category (2) outliers and identified for later removal and discussion. With the exceptions of the two outliers just noted, the variable P_2 did not change across the data set. This variable was removed from the cluster analysis as

TABLE 20
Correlation Matrix of Second Research Data Set (w/Dummy Variables)

	P_1	P_3	D_4	D_{56}	D_7
P_1	1.00				
P_3	**-0.37**	1.00			
P_4	**0.30**	-0.08	1.00		
P_{56}	-0.01	0.06	**-0.32**	1.00	
P_7	-0.21	0.21	**-0.54**	0.24	1.00

recommended by Hair et al. (2006) in order to minimize diluting the effects of the remaining variables. No other univariate outliers were noted.

Bivariate Analysis of the Second Research Data Set (w/Dummy Variables). The scatter plot shown in Figure 36 was constructed and reviewed as recommend by Hair et al. (2006). Again, all bivariate combinations that represented 5 or less data points in the research data points were examined as outliers. Seven data points were identified as outliers and removed from further analysis as category (2) outliers.

The remaining data set was examined for multicollinearity as recommended by Hair et al. (2006). A correlation matrix (Table 20) of the five remaining variables across 93 remaining data points again reveals a strong correlation between D_4 (Cost) and D_7 (Market). Correlations of r greater than or equal to 0.26 are statistically significant ($p<.01$). Again, since D_7 (Market) is a highlighted feature of the disruptive theory, it was left in the analysis – recognizing that it would likely enhance the presence of disruptive innovation in the final cluster result.

FIGURE 36
Scatterplot of Second Research Data Set (w/Dummy Variables)

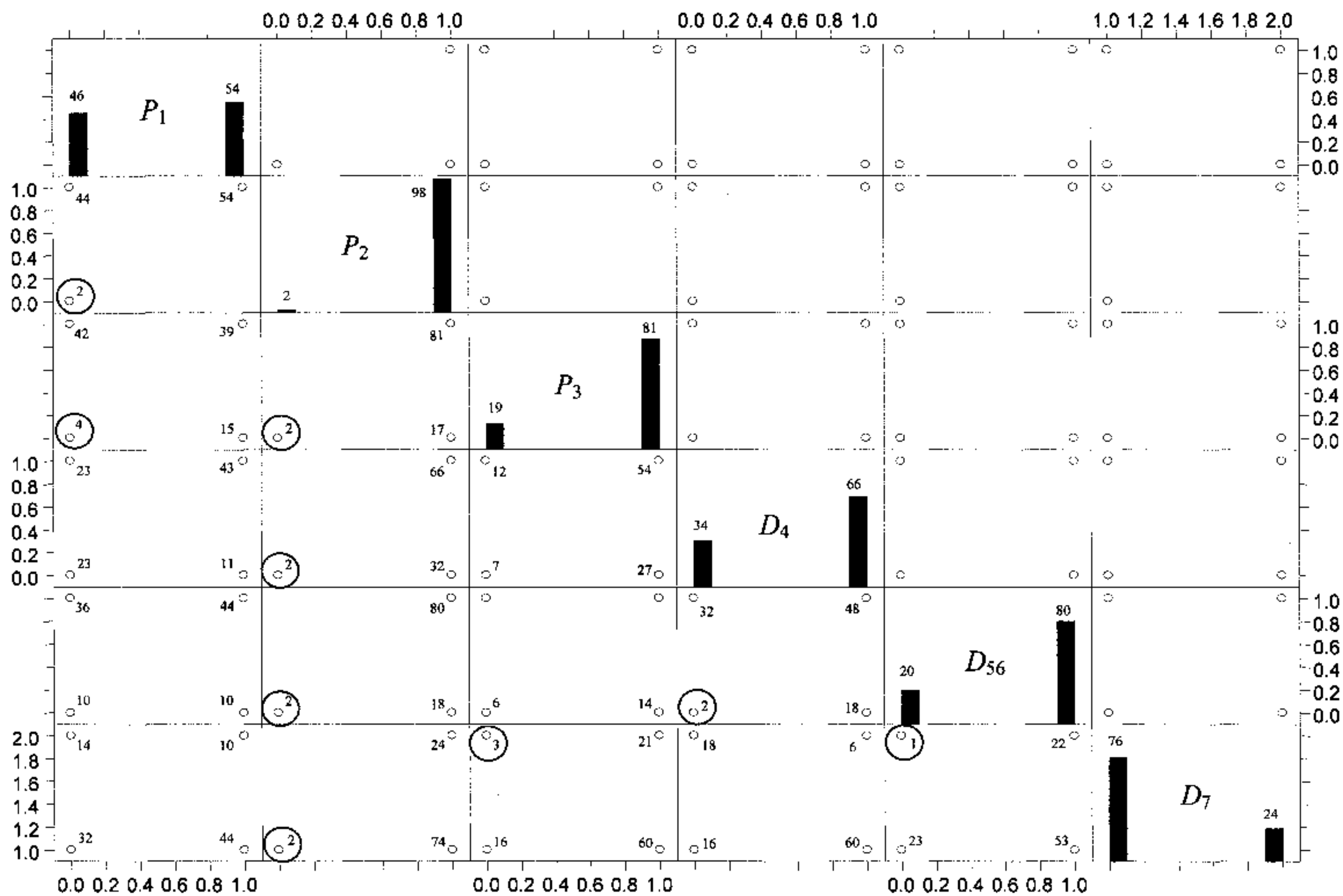
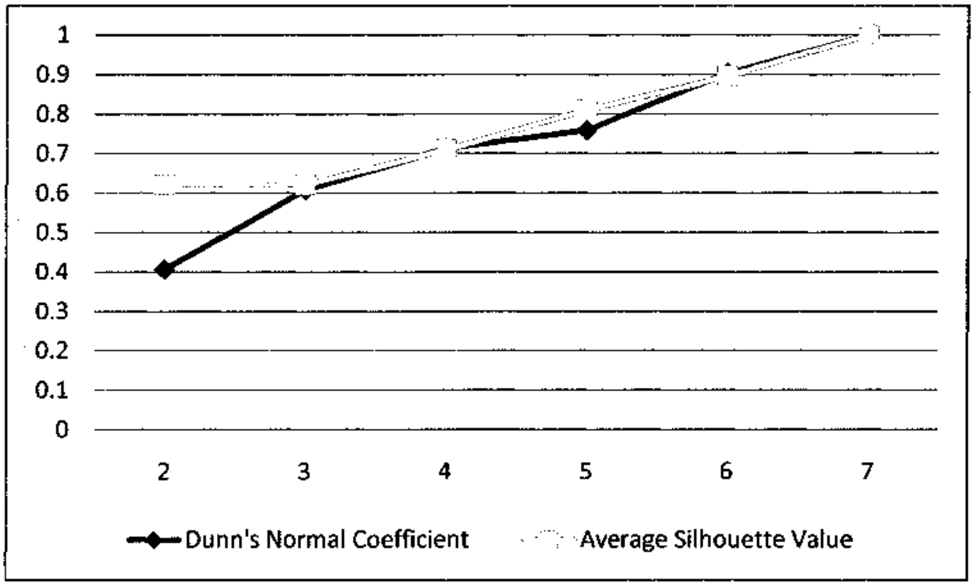


TABLE 21
Second Research Data Set (w/Disruptive Dummy Variables)

Number of Data Points	P_1 New Technology	P_2 New Core Component	P_3 New System Architecture	D_4 Performance Dummy Variable	D_{56} Performance/Cost Dummy Variable	D_7 Market Dummy Variable
22	1	1	1	1	1	a
14	0	1	1	1	1	a
12	0	1	1	0	1	b
8	0	1	1	0	1	a
7	0	1	1	1	0	a
7	1	1	0	1	1	a
6	1	1	1	1	0	a
Outliers Removed During Multivariate Analysis						
4	1	1	1	0	1	b
3	1	1	1	0	1	a
3	1	1	0	1	0	a
3	1	1	0	0	1	a
3	1	1	1	1	1	b
1	0	1	1	1	1	b
Outliers Removed During Univariate and Bivariate Analysis						
2	0	0	0	0	0	a
1	0	1	0	0	1	b
1	0	1	0	1	0	a
1	1	1	0	0	1	b
1	1	1	0	1	1	b
1	1	1	1	1	0	b

Table 21 shows the entire research data sample recoded with the dummy variables. Several of the data subsets are the equivalent of multivariate outliers. 8 of the 15 subsets number five or less in number and are removed from the cluster analysis. With the variable P_2 (New Core Component) removed, the final research data set used in the cluster analysis consisted of 76 data points and 5 variables.

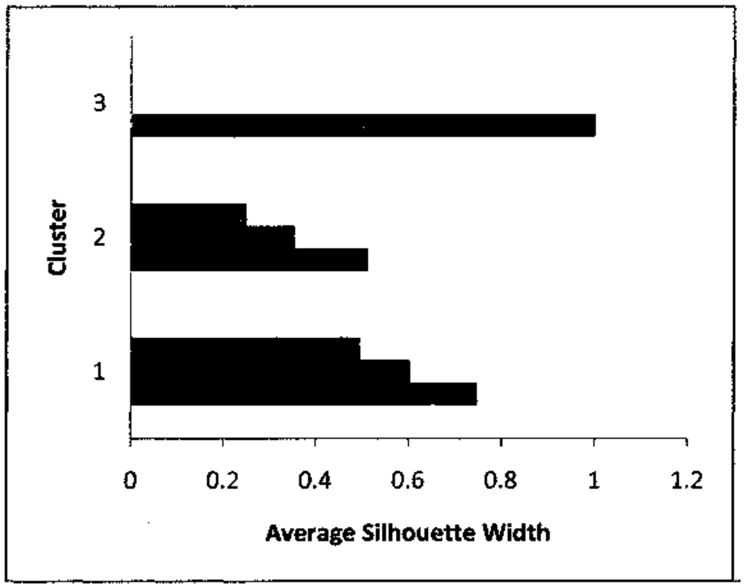
FIGURE 37
Cluster Analysis Results of the Second Research Data Set (w/Dummy Variables)



Number of Clusters (k)	Dunn's Coefficient Normalized	Average Silhouette Width
k = 2	0.41	0.62
k = 3	0.61	0.62
k = 4	0.71	0.71
k = 5	0.76	0.81
k = 6	0.90	0.90
k = 7	1.00	1.00

Cluster Analysis of the Research Sample (w/Dummy Variables). A dissimilarity matrix was constructed and analyzed using the algorithms, DAISY and FANNY, implemented in S-PLUS[tm] 8.0 for Windows. Figure 37 shows the cluster solutions that were generated. The three cluster solution appears best suited to test the hypotheses under investigation in this research, and the high average silhouette width of the three cluster solution (>0.5) indicates strong data structure and suggests high confidence in the three cluster solution (Kaufman et al., 1990). Figures 38 and 39 illustrate the three cluster

FIGURE 38
Silhouette Plot of the Second Research Data Set Three Cluster Solution



solution using silhouette widths and a projection of the first two components of a primary component analysis onto two dimensions. Tables 22 and 23 show the membership coefficients for each data point in the k=3, three cluster solution both graphically and in tabular form.

All six of the cluster solutions generated from k=2 to k=7 indicate strong data structure (average silhouette value > 0.5) with decreasing level of fuzziness. The three cluster solution was chosen because the first cluster solution that closely resembles the discontinuous cluster formed in the previous analysis and the third cluster closely represents the expected discontinuous result.

FIGURE 39
Two Dimension Representation of the Second Data Set Three Cluster Solution

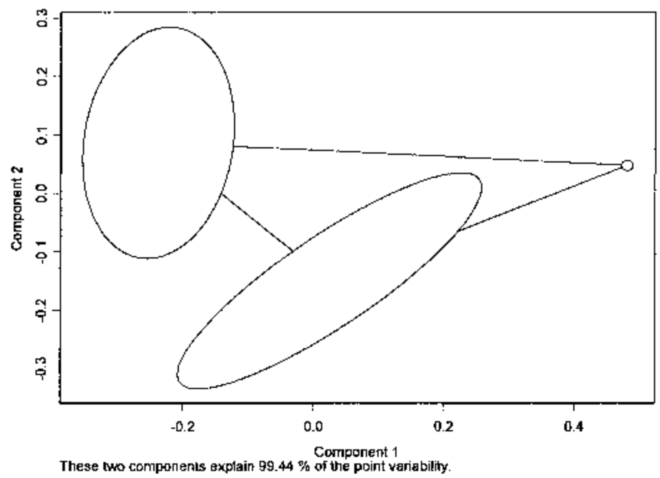


TABLE 22
Membership Coefficients of the Second Research Data Set Three Cluster Solution

Cluster Subgroups	Cluster One Membership Coefficient	Cluster Two Membership Coefficient	Cluster Three Membership Coefficient
Cluster 1			
22 Data Points	**0.97**	0.02	0.01
7 Data Points	**0.59**	0.27	0.14
6 Data Points	**0.57**	0.30	0.13
Cluster 2			
14 Data Points	0.05	**0.93**	0.02
7 Data Points	0.29	**0.56**	0.15
8 Data Points	0.24	**0.43**	0.33
Cluster 3			
12 Data Points	0.01	0.01	**0.99**

TABLE 23
Second Research Data Set Three Cluster Solution

Number of Data Points	P_1 New Technology	P_2 New Core Component	P_3 New System Architecture	D_4 Performance Dummy Variable	D_{56} Performance/Cost Dummy Variable	D_7 Market Dummy Variable
			Cluster 1			
22	1	1	1	1	1	a
7	1	1	0	1	1	a
6	1	1	1	1	0	a
			Cluster 2			
14	0	1	1	1	1	a
7	0	1	1	1	0	a
8	0	1	1	0	1	a
			Cluster 3			
12	0	1	1	0	1	b

Hypotheses Testing of the Second Research Data Set (w/Dummy Variables)

Hypothesis 4. *There is no natural grouping of discontinuous innovations where a new technology is introduced into a product's core and results in a new dominant design that significantly outperforms previous designs along established performance parameters while competing in the main market of an industry.* The entire first cluster represents 35% of the research sample and displays all four of the predicted characteristics (P_1 =1, P_2 = 1, D_4 = 1, and D_7 = a). The null of hypothesis 4 is rejected.

Hypothesis 4a. *If a natural grouping of discontinuous innovations is present, the introduction of new technology is not a necessary component.* In this analysis, all of the 35 data points in the first cluster required a new technology (P_1 = 1) to achieve the dominant design shift. The null of hypothesis 4a is rejected.

Hypothesis 4b. *If a natural grouping of discontinuous innovations is present, the introduction of a new core component is not a necessary component.* All 35 of the data points in the first cluster required the introduction of a new core component (P_2 = 1). Hypothesis 4b is rejected. However, as noted before, 98 of the original 100 data points collected displayed a new core component as a part of the change in dominant design. The two data points that did not have a change in core component, did not display design shifts. Therefore, while the hypothesis as stated is rejected, this result suggests that all shifts in dominant design require the introduction of new core components and that this characteristic is in no way unique to discontinuous innovation.

Hypothesis 4c. *If a natural grouping of discontinuous innovations is present, the improvement of performance along established trajectories is not a necessary component.* All 35 of the data points in the first cluster included the improvement of performance along established parameters (D_4 = 1). This hypothesis is rejected.

Hypothesis 4d. *If a natural grouping of discontinuous innovations is present, the introduction of the new dominant design within the main market of the industry is not a necessary component.* All 35 data points in the first cluster introduced the dominant design shift in the main market of the industry (D_7 = a). This hypothesis is rejected.

Hypothesis 5. *There is no natural grouping of disruptive innovations where a new architecture is introduced that results in a new dominant design that equals or underperforms existing designs along established parameters while shifting competition to new performance parameters (such as size or reliability) or reducing cost while competing in the low end or from an adjacent market of an industry.* The entire third cluster displays all four of the predicted characteristics of discontinuous innovation (D_3 =

1, $D_4 = 0$, $D_{56} = 1$, and $D_7 = \text{b}$). The third cluster represents 12% of the research sample and displays all four of the predicted characteristics of disruptive innovation. The null of hypothesis 5 is rejected.

Hypothesis 5a. *If a natural grouping of disruptive innovations is present, the introduction of a new architecture is not a necessary component.* All 12 of the data points in the third cluster required the introduction of a new architecture ($P_3 = 1$). Hypothesis 5a is rejected.

Hypothesis 5b. *If a natural grouping of disruptive innovations is present, the presence of a dominant design that equals or underperforms existing designs along established parameters is not a necessary condition.* All 12 of the data points in the third cluster displayed a new dominant design that equaled or underperformed existing designs ($D_4 = 0$). Hypothesis 5a is rejected.

Hypothesis 5c. *If a natural grouping of disruptive innovations is present, the improvement of performance along new parameters or the reduction in cost is not a necessary component.* All 12 of the data points in the third cluster showed improvement of performance along new parameters or the reduction in cost ($D_{56} = 1$). Hypothesis 5a is rejected.

Hypothesis 5d. *If a natural grouping of disruptive innovation is present, the introduction of the new dominant design in the low end of existing markets or within adjacent markets is not a necessary component.* All 12 of the data points in the third cluster introduced the new dominant design in a disruptive manner ($D_7 = \text{b}$). Hypothesis 5d is rejected.

Hypothesis 6. *A taxonomy constructed from shifts observed in the dominant design of established industries does not display natural clusters of innovations as predicted by the typology (Table 19) constructed from the theories of discontinuous and disruptive innovation.* Table 24 shows the entire research data set separated into the three cluster solution and the outliers removed from the cluster analysis. The variables predicted by Hypothesis 4 (discontinuous innovation) are shown on the top and the variables predicted by Hypothesis 5 (disruptive innovation) are shown on the bottom. The shading shows how each data point aligns to Hypotheses 4 and 5.

Individually, the null statements in Hypotheses 4 and 5 have been rejected. The typology has been successful in describing 47% of the research sample as modified with the dummy variables. All 35 data points of cluster 1 show all the characteristics predicted by hypothesis 4. All 12 data points of cluster 2 show all of the characteristics predicted by hypothesis 5. Clusters 1 and 3 of the taxonomy shown in Table 24 correspond with the predictions of the taxonomy constructed in the research (Table 19). The shading in Table 24 corresponds to the predicted variable states of Hypotheses 4 and 5. The null statement of Hypothesis 6 is rejected.

Discussion of the Second Research Data Set Analysis Results

As in the analysis of the first research data set, the largest cluster formed corresponds to the theories of discontinuous innovation. As stated before, this highlights the importance of the theory of discontinuous innovation as a frequent source of shifts in dominant designs for engineering and technology managers.

TABLE 24
Second Research Data Set (w/Dummy Variables)

Number of Data Points	P_1 New Technology	P_2 New Core Component	P_3 New System Architecture	D_4 Performance Dummy Variable	D_{56} Performance/Cost Dummy Variable	D_7 Market Dummy Variable
Hypothesis 4 (Discontinuous Innovation)						
	1	1		1		a
Cluster 1						
22	1	1	1	1	1	a
7	1	1	0	1	1	a
6	1	1	1	1	0	a
Cluster 2						
14	0	1	1	1	1	a
7	0	1	1	1	0	a
8	0	1	1	0	1	a
Cluster 3						
12	0	1	1	0	1	b
Hypothesis 5 (Disruptive Innovation)						
			1	0	1	b
Outliers Removed During Multivariate Analysis						
3	1	1	0	0	1	a
3	1	1	0	1	0	a
3	1	1	1	0	1	b
3	1	1	1	1	1	b
2	1	1	1	0	0	a
1	0	1	1	0	0	a
1	0	1	1	1	1	b
1	1	1	1	0	1	a
Outliers Removed During Univariate and Bivariate Analysis						
2	0	0	0	0	0	a
1	0	1	0	0	1	b
1	0	1	0	1	0	a
1	1	1	0	0	1	b
1	1	1	0	1	1	b
1	1	1	1	0	0	b
1	1	1	1	1	0	b

A comparison of the rejection of hypothesis 4a and the failure to reject hypothesis 1a emphasizes the need to use theory to interpret cluster analysis results. In the first analysis of the data set, the discontinuous cluster solution included subsets where new dominant designs emerged without the need of new technology ($P_1 = 0$). In this analysis, two subsets that were very similar to the first cluster of discontinuous innovations but with P1 = 0 were grouped in the second cluster. As a result, hypothesis 4a was rejected.

This research establishes that there are shifts in dominant designs that appear discontinuous in every way but that do not require new technology. It is up to innovation theory to define whether these shifts are discontinuous or not. As researchers, this shows the need to expand the theory of discontinuous innovation to better understand the role of new technology in achieving shifts in dominant design. As engineering and technology managers, this shows that new dominant designs that improve performance and are ready to compete in the main markets of industries do not always require the introduction of new technologies.

As before, the rejection of hypothesis 4b is tempered by the realization that essentially all shifts in dominant design displayed changes in core components of the design. The redesign of core components does not distinguish discontinuous innovation from other forms of innovation. The rejection of hypotheses 4c and 4d substantiate for engineering and technology managers that the two attributes that best define and distinguish discontinuous innovations as they cause shifts in dominant design is their ability to improve the performance of designs along expected parameters and to be competitive in the main markets of the industry.

TABLE 25
Deconstruction of Dummy Variable D_{56} within Cluster 1

		P_5 Performance along New Parameters	
		$P_5 = 0$	$P_5 = 1$
P_6 Cost	$P_6 = -1$	19 data points	3 data points
	$P_6 = 0$	-	-
	$P_6 = 1$	6 data points	7 data points

Cluster 1 can be further separated into subsets in order to examine the role of new attributes/cost (D_{56}= 0 or 1) in these shifts in dominant design. In order to interpret these results, the dummy variable D_{56} must be deconstructed into the original variables of P_5 (new attributes) and P_6 (cost). When converted back to the original variables, four combinations of the variables P_5 (new attributes) and P_6 (cost) are present (See Table 25).

This repeats the finding in the first analysis that there seem to be two cost conditions (P_6) where discontinuous innovations achieve shifts in dominant designs. First, when customers are willing to pay more for the performance features of the new design and when the new design improves performance while reducing cost. This result also suggests that new designs sometimes provide new attributes that affect competition in the main market. The introduction of Global Positioning System technology into the geophysical surveying industry and mapping industry is an example of how a new technology can improve performance while reducing cost and providing valuable new attributes for customers of the service.

> High above the earth, a constellation of satellites orbits our planet, transmitting radio signals that allow us to determine where we are on the Earth's surface. This Global Positioning System (GPS), when used according to the specified procedures, can determine positional coordinates

> to centimeter-level accuracy anywhere on the surface of the Earth. GPS has revolutionized surveying, providing latitude, longitude, and height information more quickly, inexpensively, and accurately than was possible by traditional surveying methods. (National Oceanic and Atmospheric Administration, 2007)

The rejection of hypotheses 5 thru 5d shows that the use of dummy variables was successful in highlighting disruptive innovations in a data set of shifts in dominant design. The fact that dummy variables were needed to distinguish discontinuous innovations from the remainder of the data set demonstrates how easy it is to confuse disruptive innovations with other innovations that routinely occur. All four conditional statements encoded in the dummy variables needed to be met to be included in cluster 3. This demonstrates the need for engineering and technology managers to understand the specific conditions under which disruptive innovation occurs.

The central questions of this research ask whether a taxonomy derived from a statistical sampling of shifts in dominant design can help reconcile the theories discontinuous and disruptive innovation. The taxonomy shown in Table 23 successfully classified 47 of the 100 shifts in dominant design collected in this research sample (as validated in the rejection of hypothesis 6). This taxonomy also substantiates the typology constructed from theory (research question 1.c.i) and shows specific clusters of innovation that correspond to the theories of discontinuous and disruptive innovation.

A second question asks whether there are cases where both theories seem to operate. One example of both theories operating was discovered in the pilot study. As previously discussed, the introduction of the DEC PDP-3 series minicomputer incorporated a design that contained both disruptive and discontinuous innovations. Coded with the dummy variables used in the second analysis of the research data set, the

DEC PDP-8 minicomputer would be represented by the data set [$P_1 = 1$, $P_2 = 1$, $P_3 = 1$, $D_4 = 1$, $D_{56} = 1$, $D_7 = $ b]. Three data points in Table 24 have similar coding. Further deconstructing the variables D4, D56, and D7 into the original values of P4, P5, P6, and P7, there are two examples in Table 24 that have the same data set as the DEC PDP-8.

The first example is the introduction of computer aided design software into the traditional designs services industry. The introduction of computer graphics programs started in the 1960's and displays the typical disruptive-like trajectory of a low end market innovation and continues today to provide easy to use software for home and office use (Duan, 2003). However, computer aided design became a core component of a larger transition to computer aided production engineering which helped shaped discontinuous-like competition within major industries as they competed to improve quality and reduce cost (Beit-On, 1999). This example displays aspects of both theories. The original design software was not very capable and took advantage of disruptive like market opportunities to provide low-end and new market opportunities to customers who previously had no easy access to industrial design services. However, once backed by significant industrial investment by market incumbents, the computer aided design exceeded the capabilities of traditional design methods while reducing cost in what look like a discontinuous shift in dominant design.

The second example is the transition from liquid fuel to solid fuel rockets in the guided missile and space propulsion unit manufacture. Fought (2009) describes a discontinuous sequence of innovation in the generational change of ballistic missile fuels as performance is improved and cost is reduced. The first generation of intercontinental ballistic missiles was fueled by liquid fuels which were expensive and required refueling since liquid fuels could not be stored for long periods of time. The second generation used liquid fuel with the capacity to be stored for longer periods of time. The third and current generation of ballistic missiles uses solid fuels that are relatively inexpensive, safer to store, easier to make, and provided quicker reaction times [$P_4 = 1$, $P_6 = -1$]. However, solid fuels had always existed in the low end markets of explosives from the invention of gunpowder. The improvement of solid fuel from the low end market of good enough to better than existing liquid fuels shows many of the traits of a disruptive market innovation [P_7 = b].

In each of these three cases, aspects of both discontinuous and disruptive theory are present while neither should be classified as a traditional discontinuous or disruptive innovation. Also, in a broader sense, many of the shifts in dominant design classified here as outliers share aspects of both theories. These results point to the need for researchers to expand existing theories in order to explain the how shifts in dominant designs occur when aspects of both theories are present. Engineering and technology managers should keep in mind that the theories of innovation are incomplete and many opportunities for innovation may be present even though not well described by discontinuous or disruptive theory.

A third question of this research explores whether there are examples of shifts in dominant design where neither theory seems to operate. Further examination of cluster 2 provides some insight into this question. The first two subgroups in cluster 2 have already been discussed. They appear to be innovations very similar to discontinuous innovation that did not require the introduction of new technology to achieve a shift in dominant design. The third subset appears similar to the disruptive innovations in cluster

3 but were introduced into the main market rather than in low end or new markets (P_7 = a). As before, these eight data points must be deconstructed into their original values into order to examine what these cases represent.

Three of the eight data points in cluster 2 came from shifts in dominant designs where the performance variables remained unchanged ($P_4 = 0$ and $P_5 = 0$) while the cost was reduced ($P_6 = -1$). An example of this type of shift in dominant design is the introduction of on-site manufacture of industrial oxygen and nitrogen in the industrial gas manufacturing industry. On site manufacturing provides high quality industrial gages at a reduced cost because cryogenic shipping of the industrial gas is eliminated from the process (Chapman, 1995). The first users of on-site industrial gas were the large chemical plants with high demand but improvements in on-site manufacture are expanding the market for on-site manufacture to lower end markets. These three examples resemble disruptive innovation more than discontinuous innovation. Although introduced into the main markets first, on-site manufacturing creates a disruptive business model that undermines the business of traditional centralized manufacture.

However, the remaining five data points are examples where performance along expected parameters remained the same or degraded (P_4 = 0 or -1), but main market customers were willing to pay more ($P_6 = 1$) for a new feature or attribute ($P_5 = 1$). An example of this type of innovation is the introduction of pre-packaged bagged salads into the fruit and vegetable market industry:

> As Americans spend less time preparing the meals they eat at home, the convenience of fresh-cut produce has become more important. Bagged salads (washed, cut, and ready-to-eat salads) are now a major sector of the produce industry… Growth of the fresh-cut industry may also have structural impacts. Bagged salads require substantial capital investments in plants and machinery, in excess of $20 million for a processing plant. This

> creates a significant barrier to entry, particularly when the fixed assets have relatively limited use outside of processing salad ingredients. Research and development to produce sophisticated films to manage product transpiration/respiration rates and extend shelf life is also costly (Calvin et al., 2001: 3).

Innovations like bagged salads do not produce a better salad and are therefore not discontinuous. They increase costs for the consumer and the industry (P6 = 1) and compete in the main markets of the industry (P7 = a) and are therefore not disruptive. These appear to be innovations where customers are willing to pay more for a design that is ***easier to use***. Adner & Levinthal (2001) discussed the interaction between product performance and price and introduced the concept of thresholds into the literature of innovation. The innovation of bagged salads suggests that researchers should distinguish between what a customer is willing to pay for performance or performance cost (P_4 and P_6) and what a customer is willing to pay to make a design easier to use or utility cost (P5 and P6). These utilitarian innovations [$P_4 = 0$ or -1, $P_5 = 1$, $P_6 = 1$, and $P_7 = a$] are examples where neither discontinuous nor disruptive theory seems to apply.

Table 26 lists every example from the 100 data points collected where this pattern of utilitarian innovations was observed. Admittedly, the example of the Oreo[tm] cookie in this list seems out of place; however, consider the following description:

> In the enviable position of being the No. 1 selling cookie in America since its introduction in 1912, the Oreo, made by Nabisco, East Hanover, N.J., a brand of Kraft Foods, was a true innovation — two chocolate disks with a crème filling in between. Among the first "interactive" foods, Oreos allow, in fact encourage, consumers to be creative when eating them. From dunking them in milk, twisting them apart, eating the creme first or slowly nibbling or quickly gobbling a handful, consumers can take ownership and make eating Oreos into a very individual creative experience (Toops, 2009: 6).

TABLE 26
Utilitarian Innovations

Old Dominant Design	New Dominant Design	P_1 New Technology	P_2 New Core Component	P_3 New System Architecture	P_4 Performance along Established Parameters	P_5 Performance along New Parameters	P_6 Cost	P_7 Industry Migration
Cash	Automobile Financing	0	1	1	0	1	1	a
Wafer Cookie	Sandwich Cookie	0	1	1	0	1	1	a
Intercity Bus	Charter Bus	0	1	1	0	1	1	a
U.S. Postal Service	E-File Taxes	0	1	1	0	1	1	a
DIY Salad Components	Fresh Cut Bagged Salads	0	1	1	-1	1	1	a
Carbon Paper Receipts	Carbonless Paper Receipts	1	1	1	0	1	1	a
Gas Stations Traditional Sales	Gas Stations Point of Sale Transaction	1	1	1	0	1	1	a

Perhaps there is a range of utility that encompasses this type of innovation. For designs that are difficult to use, customers may be willing to pay for easier use. For designs that are already easy to use, some customers may be willing to pay for more fun. In either case, in order to qualify as a shift in dominant design, the innovation must be able to compete in the main markets of industries.

While the typology developed from existing theory (Table 19) is largely substantiated, this research suggests it can be improved given the results of this research. Identifying the locus of innovation may not be necessary when classifying innovation. Both discontinuous and disruptive innovations used new technologies. All shifts in dominant design incorporated some change in core components. Architectural change was present in all examples of disruptive innovation observed here but is also often present in some discontinuous innovations. The factors identifying the locus of innovation do not seem to be reliable variables for the classification of innovation.

Additionally, the classification systems of innovation need to be able to describe other groups of innovations that are neither discontinuous nor disruptive. One group identified here are innovations that improve the utility of a product or service, often with an added cost for consumers. These modifications are reflected in the proposed typology shown in Table 27.

Validity of the Second Research Sample Results

The reliability of the second research sample results were tested by randomly splitting the variate into two groups and testing the resulting cluster solution for

TABLE 27
Proposed Typology for Classifying Shifts in Dominant Design

Dimensions of Typology		**Interdependent Variables**	**Discontinuous Innovation**	**Disruptive Innovation**	**Utilitarian Innovation**
Product Utility	Performance	Product Performance along Establish Parameters (D_4)	Better	Same or Worse	Same or Worse
	Performance	Customer Shift in Established Parameters or Reduced Cost (D_{56})		Yes	New Parameters with Higher Cost
Market	Existing	Where was the New Product Introduced? (D_7)	Main Industry	Low-end or New Market	Main Market

internal consistency as recommend by Hair et al. (2006). The k=3 cluster solutions of the two groups were nearly identical to each other validating the repeatability of the analysis. A series of five random data sets were constructed with a Monte Carlo approach taking care to ensure that each variable in the randomly constructed variates displayed similar characteristics to the research sample as recommend by Aldenderfer et al. (1984). A comparison of the average values for Dunn's Coefficient Normalized and Average Silhouette Width for the second analysis result and the Monte Carlo result are shown in Table 25. The Monte Carlo solution posits the hypothesis that there is no actual cluster in the data. It is interesting that a comparison of the values in Table 28 does not allow rejection of the possibility of a Type 1 error. This suggests that the methodology used here is capable of forming well defined clusters whether clusters are present or not. Fisher's exact test compares the cluster results to the mean results of the random samples. The Fisher's test indicates that the frequency of data points grouped in clusters 1, 2, and 3 were significantly larger than seen in the random data sets ($p < .01$).

TABLE 28
Comparison of the Three Cluster Solution from the Second Analysis with a Monte Carlo Three Cluster Solution

Solution	Dunn's Coefficient Normalized	Average Silhouette Width
Second Analysis Three Cluster	0.608	0.622
Ave Monte Carlo Three Cluster	0.724	0.736

Additionally, external validity of the second research data set was established with the rejection of the null hypotheses 4 and 5. Therefore, the validity of the second research sample result is based upon the demonstrated repeatability of the methodology, the proportions of the three clusters formed as compared with Monte Carlo samples and the external validity established with the theories of discontinuous and disruptive innovation.

CONCLUSIONS AND IMPLICATIONS

The use of taxonomies to test this typology highlights both strengths and weaknesses in the ability of existing theory to describe the practice of innovation. This discussion of the research study will address two remaining questions. First, how well does the data structure of the taxonomy created here support the theories of innovation (research question 2.a)? Second, how might the theories of innovation be improved to better fit the empirical data, and is new theory required (research questions 2.b)?

Discussion of the Research Study

This research began with a review of the current state of literature of innovation from the perspective of a contextual technologist (research question 1.a). The literature reviewed was organized, and several themes were developed. First, theories of component performance that classify innovations according to the price and performance of a dominant attribute were reviewed and the theory of discontinuous innovation was described. Second, theories that integrated component performance and markets were reviewed. These theories explore interactions between customer preferences in the market and the technological development of components to classify innovations. Third, theories of component performance and system architecture were reviewed. These theories introduced a view of the product itself as a system. Lastly, theories of system architecture and markets were reviewed. These theories explore interactions between the system design or architecture and the industry as a whole. It is here that the theories of disruptive innovation are located.

Next, this research built a typology by deconstructing the theories of discontinuous and disruptive innovation into their component variables. The new technology (P_1), new core component (P_2), performance along established parameters (P_4) and main market (P_7) variables best described the expected observable characteristics in discontinuous dominant designs. The new architecture (P_3), performance along expected parameters (P_4), performance along new parameters (P_5) or cost (P_6), and competition in low end and new markets (P_7) best described the expected observable characteristics in disruptive dominant designs. An integrated typology was constructed from these variables that predicted groupings of discontinuous and disruptive design shifts in a single framework. From this framework, three sets of hypotheses were formed (research question 1.b).

This research finds that the theories of discontinuous and disruptive innovation can be integrated (research question 1.c.i). The integrated typology constructed here was tested using a taxonomy constructed from a random sample of shifts in dominant design observed in North American industries. In both tests of this typology, the shifts in dominant design that appeared to be discontinuous were found both with and without the use of new technology. Additionally, nearly all the shifts in dominant designs observed in this research required some change to their core components. This suggests that the ability of the integrated typology to distinguish between discontinuous and disruptive design shifts would be strengthened by the removal of the new technology variable, P_1, and the new core component variable, P_2, from the typology (Hypothesis 1.a, 1.b. 3.b, 6.a).

The presence of disruptive innovation was not obvious in the first taxonomy created here. The theory of disruptive innovation as described in Hypothesis 2 encompasses more variety, more conditional statements, than does the theory of discontinuous innovation. As a result, the methodology was unable to distinguish any large groups (> 5 design shifts) of discontinuous innovation in the first taxonomy. Therefore, a set of dummy variables were created to focus the methodology's ability to form disruptive groups and a second taxonomy was created. The hypotheses tested in the second analysis were relabeled from 1, 2, and 3 to 4, 5, and 6 to distinguish between a test from the first analysis and a test from the second.

In the second taxonomy, a solution with three clusters was chosen to test the integrated typology. The first cluster of the taxonomy contained shifts in dominant design that have all the expected attributes of discontinuous innovation. A second cluster of the taxonomy contained shifts in dominant design that have all the expected attributes of disruptive innovation. A third cluster contained shifts in dominant design that were neither discontinuous nor disruptive. The remainder of the taxonomy contained outliers - combinations of variables that occurred so infrequently that they were removed from the cluster analysis in order to strengthen the ability of the methodology to form well defined clusters.

Contributions to the Theories of Innovation

This research found several examples where both theories seem to operate (research question 1.c.ii). It seems that the forces of innovation described in the theories of discontinuous and disruptive innovation can combine with greater variety than current theory predicts. Designs may contain more than one type of innovation. The introduction of the DEC PDP-8 introduced a design incorporating discontinuous and disruptive components. New technologies like computer aided design software may initially seem disruptive (limited capability and low end market appeal). However, in the case of computer aided design, the performance of the software grew so rapidly that it far outstripped existing technologies, a characteristic of disruptive innovation. Our theories of innovation need to evolve to describe the variety of innovation.

Daneels (2004) raised concerns over the possibility of selection bias in the small number of cases studies chosen *ex ante* in order to substantiate the claims of disruptive innovation. The same critique could be levied on the theory of discontinuous innovation. Anderson & Tushamn's (1986, 1990) research only included a small number of case studies. The results of this research strengthen the claims of the theories of discontinuous innovation (Anderson & Tushman, 1990) and disruptive innovation (Christensen, 2006) by providing further evidence of the generalizability of each theory within a relatively large research population that minimizes the likelihood of selection bias.

As stated before, existing research presents a confusing picture of how best to integrate these theories. This research proposes and validates a typology based upon interdependent variables drawn from the literature of innovation that researchers can build upon to fully integrate these theories. 47% of the research sample was identified as shifts in dominant designs that displayed all the predicted aspects of discontinuous or disruptive innovation.

This research extends the work of Gatignon et al. (2002), which suggests that innovations are best described by product complexity, locus of innovation, innovation type, and innovation characteristics. Much of the literature on discontinuous innovation (Anderson & Tushman, 2001; Dosi, 1982; Romanelli & Tushman, 1994) emphasizes the role of new technology in the emergence of new dominant designs. This research provides several examples of discontinuous-like innovation, shifts in dominant designs that improved performance and were introduced and competed directly in the main markets of industries that achieved their success largely on the basis of architectural innovation.

This research also found examples where neither theory seems to operate (research question 1.c.iii). The second analysis of the research sample found several examples where the shifts in dominant designs occurred with no improvement or degraded performance along the expected parameters of the industry ($P_4 = 0$ or -1) and customers who were willing to pay more for the new design ($P_6 = 1$). These cases are best understood through the lens of Christensen & Raynor's "jobs to be done" theory which states:

> Predictable marketing requires an understanding of the circumstances in which customers buy and use things. Specifically, customers – people and companies – have "jobs" that arise regularly and need to get done. When customers become aware of a job that they need to get done in their lives, they look around for a product or service that they can "hire" to get the job done. This is how customers experience life (Christensen et al., 2003a: 75).

In essence, Christensen & Raynor's theory describes a simple relationship between a job – the task that a customer wants to perform; a tool – the product or service that helps the customer accomplish the task; and the customer who wants to complete the task. Disruptive innovations look for circumstances where the tool exceeds the needs of a significant segment of customers and provides those customers an alternative tool that is good enough for most tasks and that is delivered with new attributes or reduced cost that competes asymmetrically with incumbent products and services.

This research contributes to the jobs theory by suggesting that researchers differentiate between the cost/benefit calculation of the tools ability to get the job done and the cost/benefit calculation of how hard it is to use the tool. Each of the innovations in Table 26 either makes it less difficult to accomplish a task or makes it more pleasurable. These innovations are labeled utilitarian because they are motivated by an improvement in the utility of the product or service.

Contributions to Practice

This research contributes to the practice of innovation by confirming the both the value and generalizability of the theories of discontinuity and disruption in the shifts of dominant design seen in industry. When all of the observable attributes of discontinuous innovation are present, engineering and technology managers should consider whether their industry is in an era of incremental change or an era of ferment as described by Anderson & Tushman (1990). They should take into account the competence enhancing or competence destroying aspects of aspects of their design that produce the improvement in performance that is characteristic of discontinuous innovations as recommended by Tushman & Anderson (1986). The success or failure of a discontinuous design project may also be affected by the complementary assets of the manager's company or industry as shown by Rothearmel & Hill (2005). Finally, managers should analyze what customers are willing to pay for performance in the industry, what Adner & Levinthal (2001) call functional utility threshold as they determine the price points of their designs.

Similarly, when all of the observable attributes of disruptive innovation are present, the prescriptions of Christensen, Anthony & Roth (2004) are most relevant:

- Begin with an analysis of the marketplace. Will customer accept a design meets or underperforms existing designs? What business models are in place? Are new models emerging that could be applied to your design?
- Evaluate the competition from the perspective of Adner's (2002) models of competition. What symmetric and asymmetric motivations are in place?
- Make strategic choices in line with your firm's abilities and motivations. If a disruptive model is chosen, evaluate the need to spin out an independent organization in order to compete against existing markets.

However, engineering and technology managers should also be aware that many times their designs may contain some but not all of the observable attributes of either theory. This research suggests that managers should distinguish designs from the innovations described by theory. The theories tend to describe situations where each design represents one innovation. However, as was shown here, designs may contain more than one innovation. In these situations, managers should consider aspects of both theories in their planning.

Limitations of the Research Study and Recommendations for Further Research

This research was limited to the ex ante descriptions of innovation that Daneels (2004) laments. Christensen (2006) explains that new theories first describe the phenomena they observe. Over time, the theory develops to be able to explain why and ultimately predict the likelihood of various events. Perhaps, individually the theories of discontinuous and disruptive innovation have reached the point that they can predict the path of some innovations, but this research has described several examples of innovations not well described by either theory. Further research will explore theories that integrate the theories of innovations and therefore improve our ability predict innovation.

This research was limited to exploring significant effects in the research population as described by the research objectives. As a result, the outliers of the research sample received little attention. Further research is intended to explore the significance of the outliers in the research sample. Additional research is also needed to integrate the perspective of contextual technology with the other perspectives of innovation as described Gopalakrishnan & Damanpour (1997).

Ethical Concerns

This research faithfully endeavors to adhere to standards and ethics for research established by Old Dominion University and the Academy of Management as described in the *Academy of Management Code of Ethics* (2005). This research does not involve human subjects, animals, biohazardous materials or radioactive materials.

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APPENDIX A: CITATION COUNTS FOR THE THEORIES OF CONTEXTUAL TECHNOLOGY USED IN FIGURE 19

This appendix explains the procedures I used to estimate the relative importance of the literature as displayed in Figure 19. Citation counts are often used to measure the impact of research articles (Sharplin & Mabry, 1985) and research journals (Podsakoff, MacKenzie, Bachrach, & Podsakoff., 2005) with a field of research. "It is well accepted that measures of citations frequency provide objective means of evaluating the impact of scholarly research on other research" (Sharplin et al., 1985: 141). Citation counts from the Institute for Scientific Information's (ISI) Social Sciences Citation Index is the most commonly used tool for measuring this variable (Colquitt & Zapata-Phelan, 2007). Unfortunately, many of the articles from our literature search and the few books cited are not included in the ISI database. Fortunately, Google Scholar ™ has proved to be a comparable source of citation analysis in the business, engineering, and social science research (Harzing, 2008). This research uses the Google Scholar ™ database to estimate the relative importance of the literature reviewed in Chapter Two

Data and Sample

The data for this analysis comes from the 20 primary research articles referenced in Chapter Two that describe the theories of radical innovation from the perspective of contextual technologists. All of the articles in this data set were found in the Google Scholar ™ database.

Procedures

Google Scholar ™ searches and categorizes papers, theses, books and articles across many research disciplines. (http://scholar.google.com/intl/en/scholar/about.html)

Search returns measure how often the searched for reference is cited by other articles in the database. The author and citation year (e.g. Abernathy & Townsend, 1975) was entered into the search field of the database. Google Scholar ™ identifies which returns are citation counts. Each citation count confirmed that the number of citations listed were associated with the desired reference article or book. Often, several citations counts were returned by the database for same research article. This appears to have occurred because a single article was sometimes coded differently in the database. A scan of some of these multiple entries indicated that they could be summed for a total citation count with great concern for double counting citations. In one case the initial author search was unsuccessful in identifying citations. In this case, the article title was used to identify the reference in the database. In cases where are large number of returns (>500) were noted, the name of the first author cited was used to further constrain the search criteria. There are three editions of Christensen's book, ***The Innovator's Dilemma***. For this case, the database was searched for all three editions. It was noted that nearly all citations were referenced to the first edition. Therefore, the citation count of the first edition was used. With the limitations cited here, the final citation count for each article is the summation of all relevant citations in the Google Scholar ™ database. The data retrieved from this procedure is displayed in Table 29.

Equation A1 was used to set the size of the circle displayed in Figure 19 of Chapter Two. This arithmetic transformation so the relative area of the circle in the figure would correspond with the size of the citation count.

$$\text{Radius of Circle Plotted (inches)} = \frac{(\text{Number of Citations})^{1/2}}{100} \qquad \text{(A1)}$$

When two references are plotted on the same time line and the same year, the larger of

TABLE 29
Citation Counts from the 20 Reference Articles

Reference	# Citations	Reference	# Citations
Abernathy & Townsend, 1975	61	Chandy & Tellis, 1998	175
Utterback & Abernathy, 1975	878	Danneels, 2002	167
Utterback & Abernathy, 1978	1284	Hermann et al., 2006	3
Tushman & Anderson, 1986	1809	Henderson & Clark, 1990	2118
Anderson & Tushman, 1990	797	Christensen, 1992	28
Adner & Levinthal, 2001	111	Christensen, 1993	121
Rothaermel & Hill, 2005	21	Christensen, 1997	2922
Murmann & Frenken, 2006	26	Adner, 2002	110
Abernathy & Clark, 1985	713	Christensen & Raynor, 2003	358
Veryzer, 1998	205	Markides, 2006	8
		Gavindarajan & Kopalle, 2006	7

the two are plotted. If the citation count is less than 100, the size of the circle is plotted at 0.1 inches in order to enhance visibility of the data point.

Discussion of Results

Obviously, references from twenty years ago have had more opportunity to be cited than articles published in 2006. However, this simplistic procedure does highlight the importance of the Tushman & Anderson's (1986) theory of discontinuous innovation and Christensen's (1997) theory of disruptive innovation in the literature of contextual technology. The results here also highlight the significance of Henderson & Clark's (1990) theory of architectural innovation.

APPENDIX B: SHIFTS IN DOMINANT DESIGN USED IN THE PILOT STUDY

1. DEC PDP-8 16 Bit Minicomputer w/core memory and integrated circuits, 1965, Minicomputer Industry

New Dominant Design. Developed as a successor to the PDP-5, The DEC PDP-8 was Digital Equipment Corporation's most popular minicomputer. Anderson & Tushman (1990) identified the PDP-8 as a discontinuous innovation because it is one of the first minicomputers to introduce the integrated circuit. Voelcker (1988), however, pointed out that the first generation of PDP-8 had only a rudimentary integrated circuit known then as the "flip chip." According to Voelcker, DEC intended to use integrated circuits modules on the first design but had difficulties making the processor work, so the first generation of PDP-8's was constructed with discrete components. However, integrated circuits became standard on the PDP-8b and contributed to improved processor speed at two-thirds the price. Customers valued the PDP-8 because of its reliability, reduced size and reduced cost. A big factor in both the increased reliability and reduced cost was DEC's introduction of an automated wire wrapping production process that eliminated the need for hand assembly.

Old Dominant Design. Packard-Bell 250 Minicomputer with solid-state circuits, 1960 (Anderson et al., 1990).

Customers. The DEC PDP-8 has been described as the "first personal computer for engineers and scientists" (Voelcker, 1988: 86) Voelcker noted that the PDP-8 became popular in industry and academia because of its reliability and reduced cost.

New Technology. (P_1 = 1) The DPD-8 introduced integrated circuits and core memories into minicomputers (Voelcker, 1988).

Core Technology. ($P_2 = 1$) The "Flip Chip" design introduced integrated circuits and core memories as new core components (Voelcker, 1988).

System Architecture. ($P_3 = 1$) The PDP-8's architecture was new compared to previous dominant designs although based on the architecture of the PDP-5. "... the PDP-8's success was due to everything coming together at the right time: a working PDP-5 architecture, new half-size modules that reduced the size of the machine, and-in place of hand assembly-wirewrapping machines for high-volume, reliable manufacturing." (Voelcker, 1988: 87)

Performance Along Established Parameters. ($P_4 = 1$) The Packard Bell had an average CPU cycle time of 12 microsecs (Computer, 1961). Anderson & Tushman (1990) document the PDP-8 CPU time as 1.6 microsecs. The DEC PDP-8 maintenance manual (1966) documents the cycle time as 1.5 microsecs. (The time of 1.5 microsecs was used to calculate the variable X4.)

Performance Along New Parameters. ($P_5 = 1$) Voelcker (1988) reports smaller size as a new attribute. The Packard Bell was 73inches high x 24 inches wide x 28 inches deep for a total of 600 lbs. The PDP-8 was 34.1 inches high x 21.5 inches wide x 21.75 inches deep for a total of 225 lbs. This reduction in size and weight is a classic example of what Christensen would call a shift in competitive value.

Cost Performance. ($P_6 = -1$) The Packard Bell 250 cost $49, 500 in 1961. The first PDP-8 cost $16,000 in 1965.

Industry. ($P_7 = c$) The PDP-8 was introduced directly into the new minicomputer industry. However, Voelcker (1988) noteed that the real popularity for the minicomputer came because it was appropriating customers who could not afford the low end of the mainframe market whose computers costs hundreds of thousands of dollars.

2. Boeing 707-120 Jet Airplane, 1958, U.S. Airline Industry

New Dominant Design. As predicted by the theory of discontinuous innovation (Anderson et al., 1990), the Boeing 707-120 was not the first jet aircraft to be purchased and offered to airline customers. The British Overseas Airway Corporation (BOAC) flew the first prototype jet on 27 July 1949 and a 36-seat version began service on 2 May 1952. While the 500 mph Comet 1 was the first, the Boeing 707-120 became the dominant design when Pan American Airlines placed orders for twenty Boeing 707s and twenty-five Douglas DC-8s. The rest of the airline industry quickly followed suit. The 707 offered quicker service (600 mph), more seats, and the potential for transatlantic flight (Davies, 1972).

Old Dominant Design. Douglas DC-7C Piston Engine Airplane, 1956. In 1956, the dominant design in aircraft manufacture was the Douglas DC-6/7 series aircraft. These two aircraft designs accounted for 408 of a total of 787 new aircraft operated by U.S. domestic and international airlines or on order as of December 31, 1955 (Air Transport Association of America, 1956). The Douglas DC-7C was a popular and comfortable piston-engine aircraft. The CD-7C had four R-3350 Wright engines with 110 seats and a cruising range of 4,250 miles and a max speed of 355 mph (Davies, 1972).

Customers. U.S. Airlines.

New Technology. ($P_1 = 1$) The Boeing 707-120 four Pratt & Whitney JT3C-6 jet engines with a total takeoff thrust of 13,500 lbs compared to the 3,250 lbs of thrust developed by the DC-7C's piston-engines (Davies, 1972).

Core Technology. ($P_2 = 1$) The new engine is a change in the core technology of an airplane.

System Architecture. ($P_3 = 0$) The basic architecture of the airplane did not change other than to make a larger body to accommodate more passengers and to take advantage of the greater power of the jet engines (Davies, 1972).

Performance Along Established Parameters. ($P_4 = 1$) The airline industry uses a productivity measure known as seat-miles that takes into account the speed of the aircraft, the number of seats, and the range of the aircraft in a given market (Davies, 1972). X4 was calculated using data from Davies (1972), the DC-7C's seat-mile productivity was roughly 60 million seat-miles per year. The Boeing 707-120's productivity was 200 million seat-miles per year.

Performance Along New Parameters. ($P_5 = 0$) No significant change in other performance factors are reported in Anderson & Tushman (1990), Davies (1972), or Air Transportation Association Annual Reports.

Cost Performance. ($P_6 = -1$) While airline costs remain relatively stable through this period, the question is how to estimate the aircraft cost. According to the 1957 edition of the Air Transportation Association Annual Report, the largest four engine airliners of 1956 cost roughly \$2M and the new four engine jet aircraft on order were \$6.25M. These figures are representative of the DC-7C and the Boeing 707-120.

However, this is a business. A business evaluates purchases for their ability to create profit. The profit of an airplane is directly related to the available seat-mile productivity since the airlines charged by the seat mile. Therefore, this research measures P_6 by estimating changes in the expected profit. The Lockheed Electra was introduced in 1959 as a turbo-prop and cost $8.70 per seat-hour (The operating costs per seat hour estimate operating costs of each aircraft per hour and divide by the number of seats). The B707-100B is representative of a jet from the same era and cost $6.93 per seat-hour. These costs were estimated for the year 1973 in Taneja (1976). This results in a 20% reduction in cost.

Industry. (P_7 = a) The Boeing 707-120 was introduced directly into the main airline industry.

3. AN/AR Series Owens Machine Bottle Manufacture, 1903, Bottle Manufacture Industry

New Dominant Design. The Owens Automatic Glass Blowing machine was the first fully automatic glass blowing machine placed into operation. It had a significant impact in industry in general because high quality glass bottles were plentiful and inexpensive. It used a system of arms and piston-powered blowers to turn the gobs of glass into bottles. It is credited with helping to stamp out child labor in the glass bottle industry (American Society of Mechanical Engineers, 1983).

Old Dominant Design. Hand blown glass bottle in a shop manned by six men and boys (American Society of Mechanical Engineers, 1983).

Customers. Glass Bottle Manufacturers

New Technology. (P_1 = 1) The automatic glass blower introduced a new technology into the industry (Anderson & Tushman, 1990).

Core Technology. (P_2 = 1) The Owens machine was revolutionary in core design as the process of producing glass bottles transitioned from hand blown to machine manufacture.

System Architecture. (P_3 = 1) The Owens machine was revolutionary in architecture as the process of glass bottle manufacture was transitioned from hand blown to machine manufacture.

Performance Along Established Parameters. (P_4 = 1) According to the American Society for Mechanical Engineering (1983), a typical team of six men and boys could hand produce 2880 bottles per day at a cost of $1.80 per bottle. The Owens AN/AR machine could produce 72,000 bottles per day and would be manned by two men on 12 hour shifts at a cost of 10 to 12 cents per gross of bottles.

Performance Along New Parameters. (P_5 = 0) While the quality and consistency of the bottles improved significantly (American Society of Mechanical Engineers, 1983), the bottle continued to serve it original purpose to the public.

Cost Performance. (P_6 = -1) Research failed to turn up cost for the machine. However, if profitability is the measure, then this innovation was very profitable reducing the cost of bottle manufacture from $1.80/bottle to the 10 cents per 144 bottles.

Industry. (P_7 = a) The Owen machine was introduced directly into the bottle making industry.

4. XEROX Telecopier 495, 1984, Digital Facsimile Machines

New Dominant Design. The first process for transmitting facsimiles was patented in 1943 (Coopersmith, 1993). Coopersmith (1993) documented early attempts to market facsimile newspapers, the use of facsimile transmission in World War II, and the first successful widespread commercial use of facsimile equipment by Western Union to supplement telegrams in the 1950s. Through 1980, U.S. manufacturers were producing analog machines that produced a page in 2-3 minutes. The digital facsimile machine has been called a discontinuous innovation (Baum et al., 1995). The XEROX Telecopier 495 (whose attributes are listed below) is considered representative of the digital facsimile equipment which replaced analog machines (Perna, 1984):

- Transmission over ordinary voice grade telephone lines.
- Compatible with earlier generations of machines (optional)
- Diagnostics
- Monitors to ensure transmission received
- Time/date/terminal ID stamp
- Automatic Dialer (optional)
- Automatic Receive
- Automatic Paper Cutter
- Transmission speed of 9600 b/s and 24 sec/page
- 9600 digital modem with lower speed compatibility
- Low bit error rate

Old Dominant Design. Group 2 Analog Facsimile Machines. Analog machines are described as smelly, slow, costly and of low quality (Coopersmith, 1993). The Group 2 machines used analog transmission and offered transmission at approximately 3 minutes per page (Baum et al., 1995).

Customers. Business for general office communication

New Technology. ($P_1 = 1$) Shift from analog to digital technology

Core Technology. ($P_2 = 1$) The digital transmission process is core to the function of the system.

System Architecture. ($P_3 = 0$) The basic architecture of the machine remained the same.

Performance Along Established Parameters. ($P_4 = 1$) Transmission speed of a single page is used as a primary established industry metric. The digital XEROX transmitted at 24 sec/page. The Group 2 standard was 180 sec/page. From a performance perspective, the Group3 XEROX machine transmitted 2.5 pages per minute. The Group 2 standard machine transmitted .33 pages per minute. These values translate to a 658% improvement in transmission speed. There were several other improvements noted such as the ability to use standard paper, automatic dialing, and an improvement in overall quality.

Performance Along New Parameters. ($P_5 = 0$) The desirable functions of the facsimile machine did not shift to new parameters.

Cost Performance. ($P_6 = -1$) The XEROX Telecopier 495 sold for between $11,995 and $15,395 in 1981 (New York Times, 1981). While this research failed to turn up a specific cost for the equipment, prices in the industry were clearly falling as each new generation of equipment was introduced (Buzzell, George, & Arkin, 1996).

Baum et al. (1995) compared the cost per month for a business to operate a group 2 and a group 3 fax machine. In 1984, there was on average a 66% savings in cost to operate a Group 3 digital machine if the company was transmitting between 10 and 20 pages a day. The cost per month to the business was used to calculate cost performance.

Industry. (P_7 = a) Each generation of facsimile machine went head to head in the office industry (Baum et al., 1995).

5. Radial Automobile Tires, 1970, Automobile Manufacturing

New Dominant Design. Sull et al. (1997) analyzed the develop of the radial tire. They note that five tire manufacturers dominated the U.S. landscape in the early 1970's: Goodyear, Firestone, Uniroyal, BFGoodrich, and General Tire. Developed first in European markets, radial tires offered many advantages. While they cost 30-50% more, their longer life translated to a lower cost per mile basis with fewer trips to tire dealers for replacements. Unfortunately, manufacture of the radial tire meant significant infrastructure and training costs in the industry and lowering profits.

Old Dominant Design. Bias Ply Automobile Tires

Customers. Automobile Manufacturers and Owners

New Technology. (P_1 = 1) In a bias tire, layers of rubber-coated fabric are embedded in the tire at an angle (Sull et al., 1997). In a radial tire, rubber coated fabric ran directly across the tire and included a layer of steel wire coated with rubber. Therefore, the belts ran perpendicular to the travel of the tire.

Core Technology. ($P_2 = 1$) The addition of the steel wire was a change in core technology.

System Architecture. ($P_3 = 1$) The requirements for construction of a radial tire were more exacting than for a bias ply tire (Sull et al., 1997).

Performance Along Established Parameters. ($P_4 = 1$) Radial tires lasted 40,000 miles vs 12,000 miles for a bias ply tire, were safer, and had better gas mileage (Sull et al., 1997).

***Performance Along New Parameters*:** ($P_5 = 0$) The desirable features of tires did not shift to new parameters.

Cost Performance. ($P_6 = 1$) Radial tires were 30-50% more expensive than bias ply tires. When combined with their longer life, radial tires translated into roughly a 50% reduction in overall cost of ownership (Sull et al., 1997).

Industry. ($P_7 = a$) The radial tire market directly competed with the bias ply market and customers forced industry leaders to adopt the radial tire at significant cost. The first major automobile to make the radial tire standard was the 1970 Ford Lincoln (Sull et al., 1997). If anything, this was a high market invasion.

6. HP ThinkJet Printer, 1984, Desktop Printer Industry

New Dominant Design. In 1984, Hewlitt Packard introduced both the LaserJet and the ThinkJet printers (HP_Virtual_Museum, 2008). The LaserJet was the ultimate office printer with high quality printing and quiet operation. Hewlitt Packard marketed the ThinkJet as a "personal printer for your personal computer"(HP ThinkJet Marketing Brochure, 1984). It offered a new method of printing thermal ink jet at reduced resolution and speed and at reduced cost. Christensen called the inkjet printer "a classic disruptive product, relative to the laser jet business" (Christensen, 1997: 116)

Old Dominant Design. Laser Printers

Customers. Personal Computer Users and Businesses

New Technology. ($P_1 = 1$) Ink Jet technology was new.

Core Technology. ($P_2 = 1$) The core technology change was from laser to ink-jet.

System Architecture. ($P_3 = 1$) Reduction in size and portability changed the architecture.

Performance Along Established Parameters. ($P_4 = -1$) Speed of the 1984 ThinkJet was 150 characters per second. Resolution was 96 dots per inch (graphic) and used a 11x12 character cell. The 1984 Laserjet printed at 8 pages a minute and with 300 dots per inch resolution. Resolution decreased by 68% and speed decreased by 78% (if one assumes roughly 2000 characters per page).

Performance Along New Parameters. ($P_5 = 1$) The Laserjet could fit on a desktop, but the ThinkJet was smaller in size at just 7 lbs. It was also portable with a battery pack. The offer of portability offered a new capability that the LaserJet could not. Also, the ThinkJet was highly valued for its quiet operation compared to dot matrix computers.

Cost Performance. ($P_6 = -1$) The Laserjet cost $3500 (HP_Computer_Museum, 2008b) while the ThinkJet cost $495 (HP_Computer_Museum, 2008a).

Industry. ($P_7 = $ c) The ink-jet provided a quality printer to a new market of computer users. It eventually invaded the laser printer market causing laser products to move up-market (Christensen & Raynor, 2003).

7. Steel Industry Minimill, 1995, Structural Steel

New Dominant Design. Christensen (1997) describes the rise of steel minimills from the manufacture of steel rebar to their head to head competition with Major U.S. Integrated Steel Mills.

Old Dominant Design. Integrated Steel Mill

Customers. Structural Steel Manufacturers

New Technology. ($P_1 = 0$) Minimills use electric arc furnaces with essentially the same processes as an integrated mill just smaller in scale. It is hard to argue that the electric arc furnace is a new technology. It has been part of the metal industry for many years. For more info see: *The Electric Furnace: Its Evolution, Theory, and Practice* by Alfred Stansfield (1914).

Core Technology. ($P_2 = 1$) Even though no new technology is involved, the electric arc is a change in the core technology of an integrated mill.

System Architecture. ($P_3 = 1$) As Christensen (1997) noted, the processes of the minimill and the integrated mill are similar though at a different scale. However, this change in scale offers new value in the production of steel. The most economical way to run an integrated plant is at full capacity for long periods of time because of the cost of heating and cooling the primary furnace. Minimills, however, can be easily stopped or started in response to market demand. This offers great economic value to steel manufacturers.

Performance Along Established Parameters. ($P_4 = 0$) The performance of the minimills lags the integrated plants but as they catch up, they capture market share.

Therefore, X4 is set at 0 to reflect their need to match industry quality. A recent industry journal compared minimills with integrated mills:

> Minimills and integrated mills are producing steel whose internal cleanliness is about the same…In physical properties, the integrated mills are better and have a wider range – but the minimills are improving in this area. In surface quality, the integrated mills have the advantage, although the minimills have improved here, too…(Triplett & Berry, 1998: 88)

Performance Along New Parameters. ($P_5 = 1$) The adaptability of the minimill process to changing economic demands is of great value to steel manufacturers.

Cost Performance. ($P_6 = -1$) Christensen (1997) estimated a 15% cost reduction in the operation of a minimill.

Industry. ($P_7 = \text{b}$) Christensen (1997) documented the rise of the minimills from rebar to structural steel.

8. 5.25 inch Hard Disk Drive, 1981, Hard Disk Drive Industry

New Dominant Design. This is the core technical disruption that the theory of disruptive innovation is built upon (Christensen, 1997; Christensen et al., 1996).

Old Dominant Design. 8 inch Hard Disk Drive

Customers. Computer manufacturers

New Technology. ($P_1 = 0$) Christensen & Bower (1996) demonstrates that essentially no new technologies were used in developing the smaller drives.

Core Technology. ($P_2 = 1$) While it is not a new technology, the 5.25 inch drive replaced the 8 inch drive.

System Architecture. ($P_3 = 1$) A new system architecture allows for the reduced cost and size.

Performance Along Established Parameters. (P_4 = -1) Both capacity and access time are significant measures of performance. The capacity of the 8-inch drive in 1981 was 60 Mbytes and the 5.25 inch drive was 10 Mbytes. The access time of the 8-inch drive was 30 msec and 160 msec for the 5.25-inch drives.

Performance Along New Parameters. (P_5 = 1) The weight of the 8-inch drive was 21 lbs and the 5.25-inch drive weighed 6 lbs.

Cost Performance. (P_6 = -1) Christensen & Bower (1996) emphasized the cost per megabyte change noting that the cost per megabyte of the 8-inch drive is $50 and $200 for the 5.25-inch drive. This analysis however is using product cost to measure P_6. The 8-inch drive cost $3000 and the 5.25-inch drive cost $2000.

Industry. (P_7 = b) Christensen demonstrated that the 5.25-inch drive was first introduced into the desktop industry before it invaded the minicomputer industry. It was his prototype for describing the low-end disruption.

9. Balloon expandable Stent Placement, 1996, Health Industry

New Dominant Design. Christensen & Raynor (2003) described the introduction of balloon angioplasty as a disruptive innovation to cardiac bypass surgery. Balloon Expandable Stent Placement (Trant, O'Laughlin, Ungerleider, & Garson, 1997) has since become a much more effective procedure in some cases and has the same disruptive earmarks that Christensen & Raynor (2003) noted.

Old Dominant Design. Cardiac Bypass Surgery

Customers. Heart Disease Patients

New Technology. (P_1 = 1) The balloon expandable stent is a new technology.

Core Technology. ($P_2 = 1$) The core technology of a stent is completely different than a cardiac bypass.

System Architecture. ($P_3 = 1$) The process and procedures are completely different arguing that this is an architectural change as well.

Performance Along Established Parameters. ($P_4 = 0$) Trant et al (1997) found stents and surgery to be statistically equal in the treatment of Branch Pulmonary Artery Stenosis.

Performance Along New Parameters. ($P_5 = 1$) The less invasive nature of the procedure is an important factor in the procedure's popularity.

Cost Performance. ($P_6 = -1$) The average total charges (including outpatient charges) were $58,068+/-$4372 for surgery and $33,809+/-$3533 for stents (Trant et al., 1997).

Industry. ($P_7 = c$) Christensen & Raynor (2003) explained that balloon angioplasty and then stent procedures were first performed "against non-consumption" in that they were first used to treat people who were not sick enough to require surgery. As the procedure improves, it now competes directly against surgery for effectiveness.

10. Internet Stock Brokers, 2000, Financial Services

New Dominant Design. Internet Stock Brokers

Old Dominant Design. Full Service Brokers

Customers. Individual Investors

New Technology. ($P_1 = 0$) The Internet already existed. The advent of online brokerage accounts developed with existing technology.

Core Technology. ($P_2 = 1$) The use of the internet to conduct stock trades introduced a core technology into the financial services model.

System Architecture. ($P_3 = 1$) The architecture of the broker interaction has changed from phone and face-to-face contact to computer based interaction.

Performance Along Established Parameters. ($P_4 = -1$) It is hard to measure a change in established parameters. The personal relationship provided by a traditional stock broker was intended to provide the customer with valued advice. The shift to an internet stock broker provided less of this traditional value exchange.

Performance Along New Parameters. ($P_5 = 1$) In the online version, the customer has access to much more information in order to make their own investment decisions. This is a completely new value experience.

Cost Performance. ($P_6 = -1$) Full Service Brokers cost approximately $150/trade while many online brokers cost about $7/trade (Claude-Gaudillat & Quélin, 2006).

Industry. ($P_7 = b$) Internet broker first invaded the discount broker industry before moving into the territory of the full service broker.

APPENDIX C: SHIFTS IN DOMINANT DESIGN IN THE FIRST RESEARCH DATA SET

Single Cluster (k=1) Solution			
Industry	**NAICS Code**	**Old Dominant Design**	**New Dominant Design**
12 Data Points with Observed Values of $P_1 = 1, P_2 = 1, P_3 = 1, P_4 = 1, P_5 = 0, P_6 = -1$, and $P_7 = a$			
Creamery Butter Manufacture	311512	Batch Processing	Continuous Processing
Sheet Metal Work Manufacturing	332322	Traditional Design	CAD/CAE
Roasted Nut and Peanut Butter Manufacture	311911	Batch	Continuous
Dairy Cattle and Milk Production	112120	LTLT Pasteurization	HTST Pasteurization
Gasoline Engine and Engine Parts Manufacturing	336312	Distributor/Rotor	Electronic Ignition
Ship Building and Repair	336611	In Hull Construction	Modular Construction
Soybean Processing	311222	Pressing	Solvent Extraction
Motor Vehicle Steering and Suspension Components Manu	336330	Dependent Front Suspension	MacPherson Strut
Animal Slaughtering	311611	Traditional	Boxed Beef
Industrial Mold Manufacturing	333511	Die Maker	CAM/Rapid Tooling
Industrial Truck, Tractor, Trailer, and Stacker Machinery Manufacturing	333924	Breakbulk Shipping	Comtainer Shipping
Hydroelectric Power Generation	221111	Pelton Impulse Turbine	Francis Reaction Turbine
7 Data Points with Observed Values of $P_1 = 1, P_2 = 1, P_3 = 1, P_4 = 1, P_5 = 1, P_6 = 1$, and $P_7 = a$			
Office Equipment Merchant Wholesalers	423420	2 Tier Buy and Sell	Lease and Service agreements
Nonfolding Sanitary Food Containers Manufacturing	322215	Paper Milk Carton	HDPE Milk Carton
Professional Organizations	813920	Face to Face networking	Internet Networking
Exam Prep and tutor services	611691	Traditional Small Group Tutor	Online Aided Small Group Tutor
Other Building Equipment Contractors	238290	Manual Door Opener	Automatic Garage Door Opener
Telephone Apparatus Manufacturing	334210	POTS	Digital ISDN
Frozen Fruit, Juice, and Vegetable Manufacturing	311411	Block Freezing	Individual Quick Freezing

SHIFTS IN DOMINANT DESIGN IN THE FIRST RESEARCH DATA SET (Continued)

Industry	NAICS Code	Old Dominant Design	New Dominant Design
6 Data Points with Observed Values of $P_1 = 1, P_2 = 1, P_3 = 1, P_4 = 1, P_5 = 0, P_6 = 1$, and $P_7 = a$			
Water Supply and Irrigations Systems	221310	Filtration	Filtration and Disinfection
Appliance Repair and Maintenance	811412	Manufacturer Training	Outsourced Training
Abrasive Product Manufacturing	327910	Organic bonded grinding wheel	Vitrified Grinding Wheel
Automotive Exhaust System Repair	811112	Standard Exhaust	Catalytic converter
Skiing Facilities	713920	Natural Snow	Machine Snow
Specialized Freight Trucking, Local	484220	Hand Lift Dump Truck	Hydraulic Lift Dump
7 Data Points with Observed Values of $P_1 = 1, P_2 = 1, P_3 = 0, P_4 = 1, P_5 = 0, P_6 = -1$, and $P_7 = a$			
Printing Ink Manufacturing	325910	Oil Based Ink	Soy Based Ink
Sheer Hosiery Mills	315111	Silk Stockings	Nylon Stockings
Support Activities for Animal Production	115210	Manual Sheep Shears	Machine Shears
Other Lighting Equipment Manufacture	335129	Carbon Bulb	Incandescent Bulb
Cut stock, Resawing Lumber, Planing Mills	321912	Circular Saw	Band Saw
Other Household Textile Product Mills	314129	Shuttle Looms	Shuttleless Looms
Iron Foundries	331511	Malleable Iron	Ductile Iron
7 (0,1,1,1,0,1,a) **7 Data Points with Observed Values of $P_1 = 0, P_2 = 1, P_3 = 1, P_4 = 1, P_5 = 0, P_6 = 1$, and $P_7 = a$**			
Amusement Park	713110	Day Park	Destination Theme
Other Insurance and Employee Benefit Funds	525190	Negligence Liability	Worker's Comp Insurance
Police Protection	922120	Constables	Police Force
Computer Training	611420	Non-Standardized training	IT Certificates
Nature Parks and Other Similar Institutions	712190	Bureau of Biological Survey	National Wildlife Refuge System
Promoters of Performing Arts, Sports, and Similar Events with Facilities	711310	Clubs/Municipal Teams	National League
Veterinary Services	541940	Cattle/Pet Doctors	General Practice

SHIFTS IN DOMINANT DESIGN IN THE FIRST RESEARCH DATA SET (Continued)

Industry	NAICS Code	Old Dominant Design	New Dominant Design
8 Data Points with Observed Values of $P_1 = 0$, $P_2 = 1$, $P_3 = 1$, $P_4 = 1$, $P_5 = 0$, $P_6 = -1$, and $P_7 = a$			
Motion Picture Theaters	512131	Single Screen	Multiplex
Direct Health and Medical Insurance Carriers	524114	Traditional Indemnity Plans	Managed Care (HMO, PPO, etc)
Commercial and Industrial Repair	811310	Corrective Maintenance	Preventive Maintenance
Facilities Support Services	561210	In-House Service	Large Scale Management Services
Building Inspections Services	541350	Decentralized Building Codes	Standardized Codes
Lessors of Nonfinancial Intangible Assets	533110	Product Line Franchise	Full Service Franchise
Regulation of Agricultural Marketing and Commodities 926140	926140	Local/Regional Boards	National Cheese Exchange
Shellfish Fishing	114112	Wild Crawfish Capture	Crawfish Aquaculture

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